CR-203668

IN-41
018 702

FINAL REPORT

EARTH SENSOR ASSEMBLY
for the
TROPICAL RAINFALL MEASURING MISSION
OBSERVATORY

NASA Contract No. NAS5-32463
CDRL No. 42B

Prepared By:

Steven S. Prince
James M. Hoover, CACM
EDO Corporation
Barnes Engineering Division
Shelton, CT 06484

Date Issued: 19 July 1995

Prepared for:

NASA Goddard Space Flight Center
Greenbelt, MD 20771

TRMM EARTH SENSOR ASSEMBLY (ESA) FINAL REPORT

Table of Contents

1	Introduction	1
2	Baseline Heritage	2
3	TRMM Specific Modifications	5
4	Major Program Milestones	8
5	Significant Discrepancy Reports (DR's)	9
Appendix A	Program CDRL Tabulation	A-1
Appendix B	Design of Objective Lens for TRMM	B-1

TRMM EARTH SENSOR ASSEMBLY (ESA) FINAL REPORT

1. INTRODUCTION

The Tropical Rainfall Measurement Mission (TRMM) will, for three years, measure rainfall rates over selected tropical areas of the Earth with a wide area coverage, resolution, and accuracy never before achieved. These measurements will provide data essential to understanding tropical precipitation processes that play a key role in the Earth's climatic changes. Components of the TRMM data system include land based rain gauges and precipitation radars, shipboard and aircraft equipment, and sensors now flying aboard satellites such as NOAA TIROS and Air Force DMSP. The key component, however, will be a satellite built and flown specifically for the purpose of making precipitation measurements: the TRMM Observatory. Planned for launch in 1995, the TRMM Observatory is a joint venture between NASA and the Science and Technology Agency of Japan; Japan will provide the Observatory's precipitation radar and will launch the satellite. NASA will provide the spacecraft, other on-board sensors, and the data collection and processing system.

EDO Corporation/Barnes Engineering Division (BED) has provided the TRMM Earth Sensor Assembly (ESA), a key element in the TRMM spacecraft's attitude control system. This report documents the history, design, fabrication, assembly, and test of the ESA.

Other Documentation:

Technical Users' Manual	CDRL 6B	Rev 1
Component Thermal Analysis	CDRL 20B	Rev 1
Component Structural Analysis	CDRL 21B	Rev 2
System Error Analysis	CDRL 22B	Rev 2

2 BASELINE HERITAGE

The Earth Sensor Assembly (ESA) Barnes' Model 13-401 is an optical infrared horizon sensor that was designed to control the attitude of an Earth orbiting satellite. The ESA is classified as a "Static" sensor because it has no moving parts. The original application of this unit was for the Air Force DMSP at an altitude of 400-500 nautical miles and later used for NOAA TIROS (31 have been launched, 8 more have been delivered). The design has been modified twice before for different altitudes. The Japanese ERS-1 & 2 (MELCO) units were delivered in 1988 and two Mars Observer units were delivered in 1991. The TRMM has, also, been modified; this time for the altitude of 350 Km. The altitude and other modifications will be discussed in Section 3.

The ESA unit uses four independent absolute radiometers to view segments of the horizon in the center of each North-East, North-West, South-East, and South-West quadrant (see Figure 2-1).

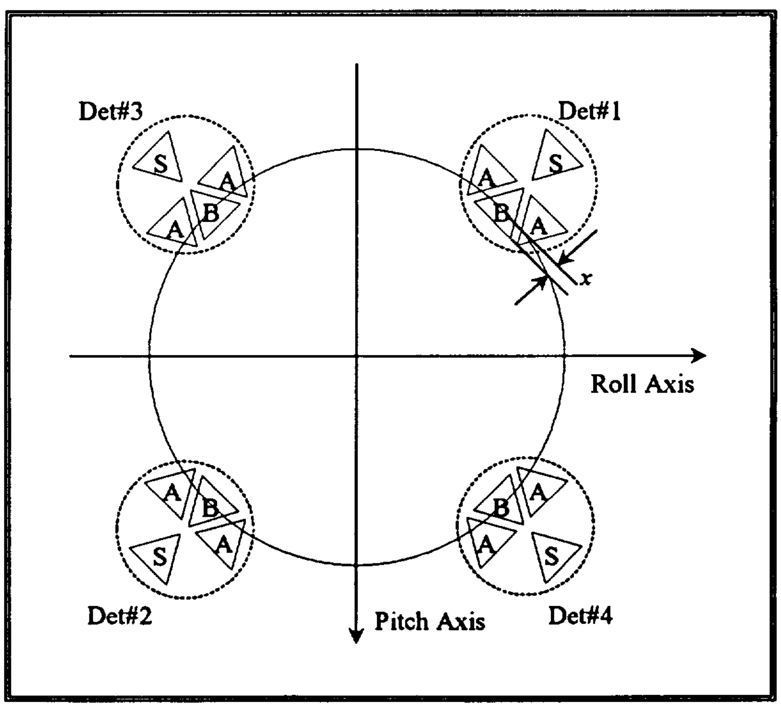


Figure 2-1 TRMM Detectors' Field-of-View

A cross section view of the ESA is shown in Figure 2-2. The four objective lenses focus the horizon segments onto four detector/cavity assemblies. Each detector/cavity assembly is equivalent to a four-channel, d-c radiometer sharing a common objective lens. Four corresponding sets of digital horizon measurement data are obtained and provided to an on-board computer for pitch and roll attitude computation.

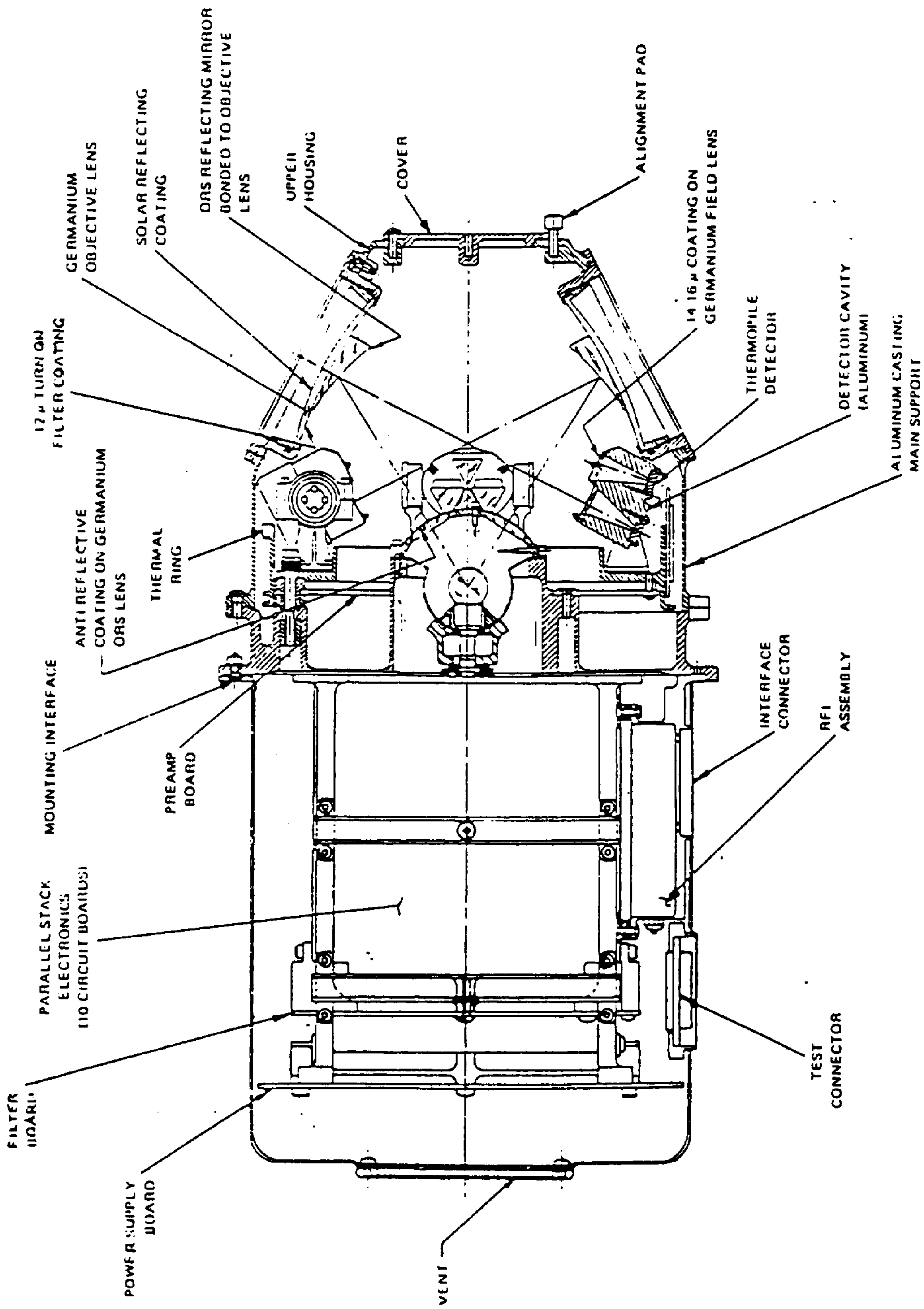
The ESA's basic principle of operation is the Barnes "double-triangle concept." A simple geometric relationship exists between the 'A' and 'B' fields of view which independently establishes the horizon with respect to the sensor for each of the four horizon segments viewed (see Figure 2-1). The measurement is tolerant of uniform radiance differences from season to season. The 'S' field of view contained in each field of view cluster provides a space radiation reference measurement.

Triangular field lenses are located at the entrance of the four optical cavities in each detector/cavity assembly. These lenses are at the field stop and restrict the view angle of the detectors to the solid angle subtended by the objective. Each objective lens projects the four triangular fields of view established by the field lenses toward the earth's horizon as shown in Figure 2-1. Bandpass filters are deposited on the field lenses to limit the sensitivity of each optical channel to energy in the 14 to 16 micron spectral band (the CO_2 band).

The 12 detector outputs are multiplexed through a single AC coupling capacitor to a single amplifier (minimizes differential drift), and then DC restored. The resulting amplified waveform is fed to a dual slope integrator which integrates the ground reference before a detector with a gain of -1/2, the detector output with a gain of 1, and the ground reference after the detector with a gain of -1/2. The final integrated signal is discharged by a reference current while a clock controlled counter determines the time to the zero crossing. The digital number of the counter at zero crossing is the "counts" reported to the spacecraft interface.

All the 13-401 ESA's have these common characteristics the look down angle is changed to accommodate altitude differences and the interface circuitry to accommodate spacecraft specific requirements.

Figure 2-2
Cross Section View Earth Sensor Assembly



3 TRMM Specific Modifications

The TRMM operates differently than the baseline TIROS/DMSP sensor. These differences required design modification in five areas briefly described below and detailed in the PDR & CDR data packages:

3.1 Reduced operating altitude - The look down angle must be changed (lens wedged) to change the altitude from 800 Km to 350 Km. The casting of the ESA's "helmet" sets the optical axis of each objective lens/detector cavity system to 62.6 degrees. At 350 Km the Earth subtends 146 degrees so that each exterior look down angle should be set to 73 degrees. Rather than change anything inside the ESA, the objective lens is designed and built with prismatic wedge to deviate the line of sight the extra 10.4 degrees. The inside radius of curvature remains the same to interface with the ORS mirror, and the outside surfaces radius of curvature is slightly changed to allow for the change in lens thickness. (see Design of Objective Lens for TRMM - Appendix B.)

3.2 Dual channel operation - The baseline system is standby redundant. The system is designed such that the independent sides <u>cannot</u> be operated simultaneously. The TRMM requirement is for active redundancy. This required a change in command circuitry and the synchronization of the normally independent channels. The detectors are common to both channels and the multiplexing of the detectors to the single preamplifier in each channel introduces small glitches which are synchronized to the multiplexing. If the sides are not in lock-step with each other the glitches of one will be in the data taking time interval of the other and erroneous data will result. This was implemented on the A5 Logic & Control board.

3.3 Fully redundant telemetry - One channel at a time operation allowed sharing of output pins in the connector interface. The RFI assembly where the connector enters the ESA had to be modified to have 52 filter feed thrus which required a major geometry change. The A4 ORS & REF TLM and the A14 Interface & Misc Boards were modified to have separate telemetry paths.

3.4 Five volt telemetry - The output to the spacecraft had been 0-10 volts signals from the spacecraft provided 10 volt bus. The interface had to be changed to 0-5 volts from an internally generated source. The A4 ORS &

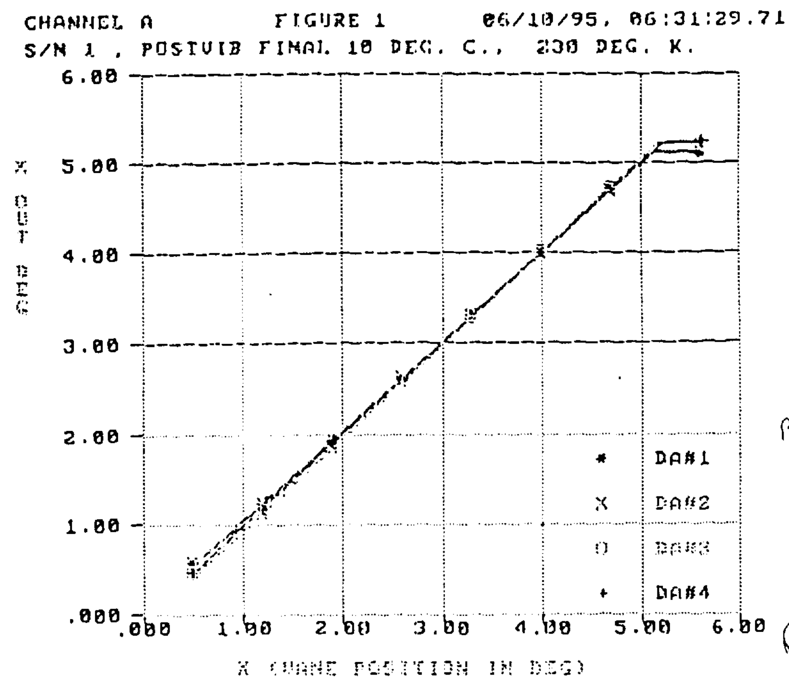
REF TLM and the A14 Interface & Misc Boards were modified to operate from the 5 volt reference rather than the 10 volt I/F bus.

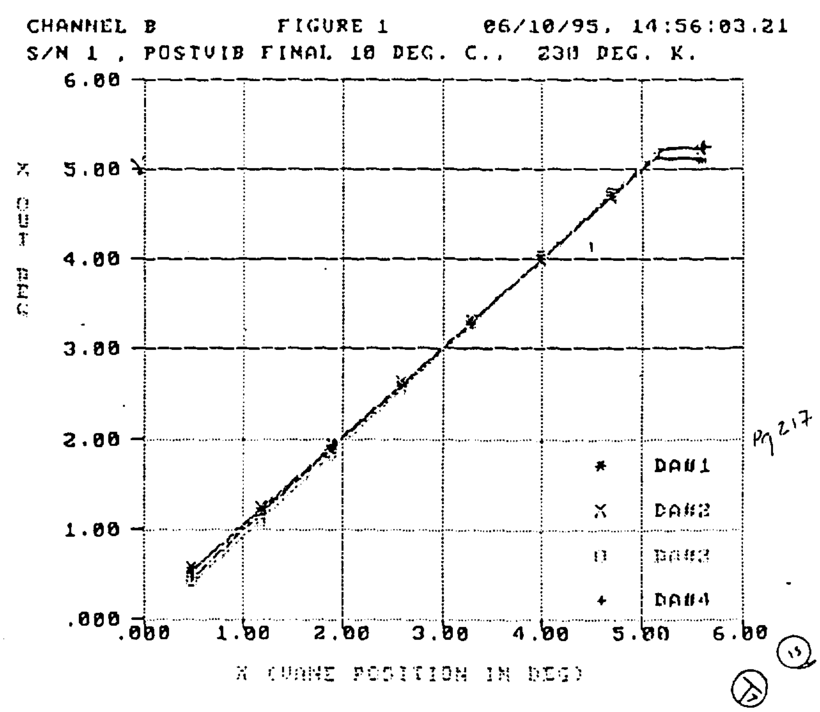
3.5 14 bit digital conversion - The baseline unit uses a 12 bit counter to encode the radiometric data as the dual slope integrator is run-out.. The TRMM required 14 bits which required an increase in the clock speed from 396 Khz to 1.6 Mhz and an increase in the counter size (effected on the A6 Logic & Clock board). The output buffer had always been 16 bits (over-range bit, sign bit, 12 data magnitude, 2 unused), the unused bits were now used as magnitude bits.

3.6 PERFORMANCE SUMMARY

PARAMETER	SPECIFIED	ACTUAL
SIZE	<20 cm X 35 cm	18.5 cm X 33.2 cm
WEIGHT	<5 Kg	4.2 Kg
POWER	<8.5 watts	7 watts
LINEARITY	<0.1 degree	see figure
ACCURACY	< 0.08 +/- 7 % of att.	see figure
NOISE	<16 counts	<4 counts

Figure 3-1
Final Transfer Functions @ 10 C
Demonstrate Accuracy & Linearity





4 MAJOR PROGRAM MILESTONES

The program proceeded on schedule through the beginning of fabrication. Two DR's in the fabrication area discussed in Section 5 slowed the progress toward Proto-Flight Testing (PTP). Unforeseen difficulties with the EMI conducted susceptibility test hindered the progress in PTP. However, PTP start to shipment was scheduled for 2 months and from EMI passing (beginning of PTP) to shipment was 2 months.

MILESTONE	PLANNED DATE	ACTUAL	
Kickoff	04/93	04/16/93	
GSFC/BED Brassboard Testing	N/A	07/93	
PDR @ GSFC	08/93	08/19/93	
CDR	11/93	11/17/93	
Beginning of Fabrication	04/94	04/94	
Beginning of System Integration		02/95	(1
Beginning of PTP	09/94	03/95	
EMI Failure		03/15/95	(2
Resume PTP (EMI passes)		04/27/95	
Completion of Testing		06/14/95	(3
Shipment	11/94	06/19/95	

NOTES:

1) Error in the A7 Logic Board layout determined August 94 set the program schedule back (as noted in the monthly reports). The error in the A6 Logic/Clock Board discovered later, at electronic stack integration January 95, delayed System Integration to February 95. Total slip for these two design flaws was 6 months.

2) EMI Conducted Susceptibility Testing was at a higher level than heritage designs had previously passed. Prior success resulted in insufficient attention paid to this area during the design phase. Ultimately, an L-C network was incorporated into the RFI assembly to reject the conducted interference, but a month and a half of schedule was consumed.

3) During PTP the trim of the unit shifted after vibration. The unit was opened cleaned, re-trimmed, re-vibrated, and continued PTP (see discussion Section 5). Loss of schedule approximately 1 week.

5 SIGNIFICANT DISCREPANCY REPORTS (DR's)

The program has had only 4 discrepancies of note, two during the design phase discovered in fabrication, and two in the Proto-flight Test phase. These DR's are discussed below.

Fabrication

A7 Logic Board layout (Aug 94)

Board artwork did not reflect the schematic. Differences were 1) U15 missing, 2) U12-pin 1 incorrectly wired to E15, and 3) E26 incorrectly shorted to E25. The design error required scrapping the boards. They were re-designed, re-purchased, re-populated,and re-tested. Reference ECN 2573-E-416.

A6 Logic/Clock Board layout (Jan 95) IPE 7505

Board was designed with insufficient clearance for stand-off. A collar/spacer is located in the center of the board through which a skewing rod is placed. This collar/spacer once installed comes in contact with (overlaps) a nearby trace. Once assembled into the electronic stack the circuit will be shorted to ground via the skewing rod. The repair cut trace to isolate it and the circuit reconnected with jumpers. Reference D1153-010B. No overstress of board occurred.

Testing

PTP EMI Test (Mar 95) FTI 2789

System failed conducted susceptibility at the 1 volt RMS level,and CE02. Previous unit (MELCO) had passed 1 volt peak-to-peak and the other test levels. Insufficient design attention was paid to this critical area. The repair installed ferrite beads on power lines and returns in the RFI assembly to reject the conducted interference. The retest passed specification. Reference ECP E1153-014.

Trim shift after vibration (May 95) FTI 2803

After vibration testing, the operating point of the 3B field shifted. The effect was caused by a change in the effective trim of the unit by a very small amount of residual contaminating on an ORS lens in the optical head. Following a through cleaning the unit was revibrated and, and continued through PTP.

APPENDIX A

PROGRAM CDRL TABULATION

Run Date: 07/19/95

APPENDIX A

TRMM STATIC ESA DELIVERABLES STATUS REPORT

Indexed by: Item Sequence

Ref: Prime Contract NAS5-32463
Dated 14 April 1993

CATEGORY CODES:
A - For GSFC Approval
I - For GSFC Information
R - For GSFC Review

GENERATED per S.O.W. Paragraph 3.6

NOTE: ALL DUE DATES ARE RECEIPT AT NASA GODDARD DATE.

cc: J. Hoover (Seq. & Due Date)
C. Thompson (Due Date)
Monthly Report (Sequence)

ITEM NO	REFERENCE CONTR	SOW	TITLE DESCRIPTION	CATEGORY & QTY	CDG. DEPT	CONDITION	CONTRACT DUE DATE	CURRENT ESTIMATE	BARNES DELIVERABLE ACTIVITY: REPORT/PART NUMBER	REV	DATED	SENT	LTR SER	DATE NASA/GSFC APPROVED	APPROVAL LETTER SERIAL	COMMENTS
A			===============================		.			99								
A			HARDWARE		.			99								
A			===============================		.			99								
1A		1.1	Earth Sensor Assembly (ESA)	1	.		12/ 1/94		Shipper #			5/22/95	DD-250	5/22/95		
2A		11.0	Shipping Container for ESA	1	.	with ESA	12/ 1/94		Shipper #			5/22/95	DD-250	5/22/95		
3A		9.1	Test Set w/ GSE Software		.											Reqmt deleted - Amend 6
4A		9.2	Detector Stimulus		.				Shipper #			6/22/95	DD-250	6/22/95		
5A		9.3	Detector Simulator		.				Instruction Manual		7/19/94	7/19/94	1153-108	5/22/95		
5A		9.3	Detector Simulator						Simulator Report		4/ 5/95	4/ 5/95	1153-207			
6A		6.0	ESA Drill Template		.											Reqmt deleted - Amend 5
7A		6.0	Connector Savers	1	.	with ESA	12/ 1/94		Shipper #			6/22/95	DD-250	5/22/95		
8A		6.0	Mating Connector	1	.		6/ 1/94				8/01/94	8/02/94	1153-114	6/22/95		
9A		11.0	Shipping Container for GSE		.	with Test Set										Reqmt deleted - Amend 11
B			===============================		.											
B			TECHNICAL DOCUMENTATION/REVIEWS		.											
.			===============================		.											
2B	C.2	3.2	Monthly Status Report - Apr 93	I-5	PM		5/15/93		#1		5/21/93	6/21/93	1153-09	info	n/a	
2B	C.2	3.2	Monthly Status Report - May 93	I-5	PM		6/15/93		#1		5/21/93	5/21/93	1153-09	info	n/a	
2B	C.2	3.2	Monthly Status Report - Jun 93	I-5	PM		7/15/93		#2		7/16/93	7/19/93	1153-14	info	n/a	
2B	C.2	3.2	Monthly Status Report - Jul 93	I-5	PM		8/15/93		#3		7/14/93	9/20/93	1153-29	info	n/a	
2B	C.2	3.2	Monthly Status Report - Aug 93	I-5	PM		9/15/93		#4		9/14/93	9/20/93	1153-30	info	n/a	
2B	C.2	3.2	Monthly Status Report - Sep 93	I-5	PM		10/15/93		#5		10/21/93	10/21/93	1153-37	info	n/a	
2B	C.2	3.2	Monthly Status Report - Oct 93	I-5	PM		11/15/93		#6		12/15/93	12/15/93	1153-49	info	n/a	
2B	C.2	3.2	Monthly Status Report - Nov 93	I-5	PM		12/15/93		#7		12/15/93	12/15/93	1153-50	info	n/a	
2B	C.2	3.2	Monthly Status Report - Dec 93	I-5	PM		1/15/94		#8		2/15/94	2/16/94	1153-60	info	n/a	
2B	C.2	3.2	Monthly Status Report - Jan 94	I-5	PM		2/15/94		#9		2/15/94	2/16/94	1153-60	info	n/a	
2B	C.2	3.2	Monthly Status Report - Feb 94	I-5	PM		3/15/94		#10		3/15/94	3/15/94	1153-64	info	n/a	
2B	C.2	3.2	Monthly Status Report - Mar 94	I-5	PM		4/15/94		#11		4/15/94	4/15/94	1153-69	info	n/a	
2B	C.2	3.2	Monthly Status Report - Apr 94	I-5	PM		5/15/94		#12		5/15/94	5/16/94	1153-83	info	n/a	
2B	C.2	3.2	Monthly Status Report - May 94	I-5	PM		6/15/94		#13		6/15/94	6/15/94	1153-92	info	n/a	
2B	C.2	3.2	Monthly Status Report - Jun 94	I-5	PM		7/15/94		#14		7/14/94	7/14/94	1153-106	info	n/a	
2B	C.2	3.2	Monthly Status Report - Jul 94	I-5	PM		8/15/94		#15		9/09/94	9/09/94	1153-117	info	n/a	
2B	C.2	3.2	Monthly Status Report - Aug 94	I-5	PM		9/15/94		#16		9/15/94	9/15/94	1153-129	info	n/a	
2B	C.2	3.2	Monthly Status Report - Sep 94	I-5	PM		10/15/94		#17		10/12/94	10/12/94	1153-126	info	n/a	
2B	C.2	3.2	Monthly Status Report - Oct 94	I-5	PM		11/15/94		#18		11/15/94	11/15/94	1153-147	info	n/a	
2B	C.2	3.2	Monthly Status Report - Nov 94	I-5	PM		12/15/94		#19		12/14/94	12/14/94	1153-156	info	n/a	
2B	C.2	3.2	Monthly Status Report - Dec 94	I-5	PM		1/15/95		#20		1/11/95	1/11/95	1153-159	info	n/a	
2B	C.2	3.2	Monthly Status Report - Jan 95	I-5	PM		2/15/95		#21		1/15/95	1/15/95	1153-175	info	n/a	
2B	C.2	3.2	Monthly Status Report - Feb 95	I-5	PM		3/15/95		#22		3/20/95	3/20/95	1153-196	info	n/a	
2B	C.2	3.2	Monthly Status Report - Mar 95	I-5	PM		4/15/95		#23		4/25/95	4/25/95	1153-217	info	n/a	
2B	C.2	3.2	Monthly Status Report - Apr 95	I-5	PM		5/15/95		#24		5/23/95	5/23/95	1153-230	info	n/a	
2B	C.2	3.2	Monthly Status Report - May/Jun 95	I-5	PM		6/15/95		#25 - FINAL		7/ 5/95	7/ 5/95	1153-262	info	n/a	
3B		3.5	Class I Changes	A-5	QC	Within 10 days of issue	as req	/ /	ECP 1153-14		4/19/95	4/19/95	1153-213	4/21/95	none	Preliminary of 914

ITEM NO	REFERENCE CONTR SOW	TITLE DESCRIPTION	CATEGORY & QTY	COG. DEPT	CONDITION	CONTRACT DUE DATE	CURRENT ESTIMATE	BARNES DELIVERABLE ACTIVITY REPORT NUMBER	REV	DATED	SENT	SERIAL	DATE NASA/GSFC APPROVED	APPROVAL LETTER SERIAL	COMMENTS
30	3.3	Class I Changes	A-5	QC	Within 10 days of issue	as req		ECP 1153-14		4/25/95	4/25/95	1153-218	4/28/95	none	
40	3.5	Configuration Management Plan	A-5	Cnfig	2 wks prior CDR	11/ 2/93		none		10/22/93	10/22/93	1153-38	07/27/94	none	
50	4.1	Interface Control Document (Prelim)	A10	PM	2 wks prior PDR	8/ 3/93		none			3/12/93	1153-21	11/04/93	none	
50		Interface Control Document (Final)	A10	PM	2 wks prior CDR	11/ 2/93		none		1/14/94	1/14/94	1153-55	11/17/94	none	
50		Interface Control Document (FINAL)	A10	PM				none		12/ 7/94	12/ 7/94	1153-151	5/19/95		
50		Interface Control Document (FINAL)	A10	PM				DAP-124		6/19/95	6/19/95	1153-259	6/19/95		Final
60	4.1	ESA Technical User's Manual (DRAFT)	R50	PM	with hardware delivery	12/ 1/94	/ /			3/31/95	3/31/95	1153-203	review	n/a	
50		ESA Technical User's Manual (FINAL)						none		5/19/95	5/19/95	1153-259	review	n/a	
70	4.2	Manufacturing Drawings	R-3	PM	2 wks prior CDR	11/ 2/93		various	vari	various	11/10/93	1153-43	review	n/a	
80	4.3.1	Electrostatic Discharge Cont Plan	A-5	PM	2 wks prior PDR	8/ 3/93		none			8/04/93	1153-18	11/04/93	none	
90	10.0	Q. A. Implementation Plan	A-5	QC	30 days after award	5/14/93		none			7/22/93	1153-15	11/04/93	none	
90	10.0	Q. A. Implementation Plan	A-5	QC	Resubmittal			none			1/13/95	1153-152	1/13/95		
100	4.3.2	Comp.Part Radiation Analysis (Prel)	R-5	Rel	2 wks prior PDR	8/ 3/93		none			8/04/93	1153-18	11/04/93	none	w/ GSFC comments 7/27/94
100	4.3.2	Comp.Part Radiation Analysis(Final)	R-5	Rel	2 wks prior CDR	11/ 2/93		none	I	11/08/93	11/10/93	1153-43	11/17/94	n/a	"reviewed"
110	4.3.2	Parts Application Stress Analysis	R-5	Rel	2 wks prior CDR	11/ 2/93		none		5/23/94	5/23/94	1153-86	review	n/a	
110	4.3.2	Parts Application Stress Analysis	R-5	Rel				none		3/29/95	3/29/95	1153-202	review,	n/a	clarify NASA questions of 3/24
120	4.3.2	Worst Case Analysis	R-5	Rel	2 wks prior CDR	11/02/93		none	init.	11/08/93	11/10/93	1153-43	review	N/A	w/ GSFC comments 7/27/94
120	4.3.2	Worst Case Analysis	R-5	Rel	2 wks prior CDR			none	A	9/19/94	9/19/94	1153-131			
130	4.3.2	EEE Parts List (Prelim)	R-3	Rel	2 wks prior PDR	08/03/93		none			8/05/93	1153-19	11/04/93	none	w/ GSFC comments
130	4.3.2	EEE Parts List (Final)	A-3	Rel	2 wks prior CDR	11/02/93		none	R2	11/08/93	11/10/93	1153-43	07/27/94	none	Reviewed 11/17/94
140	4.3.2	Non-Standard Part Approval Requests	A-3	Rel	60 days prior to procurement	as req		none			8/16/93	1153-22		N/A	
140	4.3.2	Non-Standard Part Approval Requests	A-3	Rel	60 days prior to procurement	as req		NSPAR 1153-17			9/ 9/93	1153-xxx			Withdrawn 3/3/95 1153-192
140	4.3.2	Non-Standard Part Approval Requests	A-3	Rel	60 days prior to procurement	as req		NSPAR 1153-22			9/ 9/93	1153-xxx			Withdrawn 3/3/95 1153-193
140	4.3.2	Non-Standard Part Approval Requests	A-3	Rel	60 days prior to procurement	as req		NSPAR 1153-37			5/09/94	1153-77	07/27/94	none	
140	4.3.2	Non-Standard Part Approval Requests	A-3	Rel	60 days prior to procurement	as req		NSPAR 1153-23			5/13/94	1153-81	07/27/94	none	
140	4.3.2	Non-Standard Part Approval Requests	A-3	Rel	60 days prior to procurement	as req		1153-27,-28,-29,-30			5/05/94	1153-80	07/27/94	none	
140	4.3.2	Non-Standard Part Approval Requests	A-3	Rel	60 days prior to procurement	as req		NSPAR 1153-039			5/10/94	1153-91	N/A	N/A	Withdrawn 1153-149
140	4.3.2	Non-Standard Part Approval Requests	A-3	Rel	60 days prior to procurement	as req		NSPAR 1153-040			6/20/94	1153-97	N/A		Withdrawn 1153-179 2/29/95
140	4.3.2	Non-Standard Part Approval Requests	A-3	Rel	60 days prior to procurement	as req		NSPAR 1153-041			6/24/94	1153-100	11/17/94	none	
140	4.3.2	Non-Standard Part Approval Requests	A-3	Rel	60 days prior to procurement	as req		NSPAR 1153-025			6/28/94	1153-101	11/17/94	none	
140	4.3.2	Non-Standard Part Approval Requests	A-3	Rel	60 days prior to procurement	as req		NSPAR 1153-043			7/22/94	1153-110	10/24/94	none	
140	4.3.2	Non-Standard Part Approval Requests	A-3	Rel	60 days prior to procurement	as req		NSPAR 1153-013A,014A			10/ 4/94	1153-135	11/17/94	none	
140	4.3.2	Non-Standard Part Approval Requests	A-3	Rel	60 days prior to procurement	as req		1153-011A,-012A,044			10/12/94	1153-137	11/17/94	none	
140	4.3.2	Non-Standard Part Approval Requests	A-3	Rel	60 days prior to procurement	as req		NSPAR 1153-040A			11/ 2/94	1153-144	3/ 6/95		Being reviewed 11/17/94
150	4.3.2	DPA Procedures & Requirements	A-3	Rel	30 days prior use	/ /		none		03/18/94	3/18/94	1153-62	07/27/94	none	
160	4.3.3	Inorganic Materials List (Prelim)	R-3	Rel	2 wks prior PDR	8/ 3/93		none		-	3/19/93	1153-20	11/04/93	none	w/ GSFC comments
160	4.3.3	Inorganic Materials List (Final)	A-3	Rel	2 wks prior CDR	11/ 2/93		none	A	9/30/93	11/10/93	1153-43	11/17/94	none	
170	4.3.3	Materials/Usage Agreements	A-3	Rel	As generated	as req		none		1/19/94	1/19/94	1153-56	07/27/94	none	
180	4.3.3	Material/Process List (Prelim)	R-3	Rel	2 wks prior PDR	8/ 3/93		none			8/10/93	1153-20	11/04/93	none	w/ GSFC comments
180	4.3.3	Material/Process List (Final)	A-3	Rel	2 wks prior CDR	11/ 2/93		none	A	9/30/93	11/10/93	1153-43	11/17/94	none	7/27/94 approved part
180	4.3.3	Material/Process List (FINAL)	A-3	Rel	2 wks prior CDR			2573-CDRL-180	A	June 94	06/20/94	1153-96	6/19/95	none	
180	4.3.3	Material/Process List (Updates)	A-3	Rel	As generated	as req		none		9/23/94	9/23/94	1153-124	6/19/95	none	To approve M/P list
190	4.3.3	Limited Life List (Prelim)	R-3	Rel	2 wks prior PDR	8/ 3/93		none			8/04/93	1153-18	review	n/a	
190	4.3.3	Limited Life List (Final)	A-3	Rel	2 wks prior CDR	11/ 2/93	12/29/93	none		1/13/94	1/13/94	1153-54	11/17/94	none	
200	4.3.5	Comp. Thermal Analysis (Prelim)	R-5	Rel	2 wks prior PDR	8/ 3/93		none			8/04/93	1153-18	review	n/a	
200	4.3.5	Comp. Thermal Analysis (Final)	R-5	Rel	2 wks prior CDR	11/ 2/93		none	1	11/09/93	11/10/93	1153-43	review	n/a	
200	4.3.5	Comp. Thermal Analysis (Update)	R-5	Rel				none		10/19/94	10/19/94	1153-139	review	n/a	CDR Action Item No. 5
210	4.3.6	Comp. Structural Analysis (Prelim)	R-5	Rel	2 wks prior PDR	8/ 3/93		none			8/05/93	1153-19	review	n/a	
210	4.3.6	Comp. Structural Analysis (Final)	R-3	Rel	2 wks prior CDR	11/ 2/93		none	1	11/09/93	11/10/93	1153-43	review	n/a	
220	4.3.7	Error Analysis (Prelim)	R-5	PM	2 wks prior PDR	8/ 3/93		none			8/05/93	1153-19	review	n/a	

ITEM NO	REFERENCE CONTR	SOW	TITLE DESCRIPTION	CATEGORY & QTY	COG. DEPT	CONDITION	CONTRACT DUE DATE	CURRENT ESTIMATE	DARNES DELIVERABLE ACTIVITY REPORT NUMBER	REV	DATED	SENT	SERIAL	DATE NASA/GSFC APPROVED	APPROVAL LETTER SERIAL	COMMENTS
220		4.3.7	Error Analysis (Final)	R-5	PM	2 wks prior CDR	11/ 2/93		none	1	11/08/93	11/10/93	1153-43	review	n/a	
220		4.3.7	Error Analysis (Final)	R-5	PM	2 wks prior CDR			none	1	9/29/94	9/29/94	1153-133	review	n/a	Resubmittal-GSFC lost original
230		5.2.1	Preliminary Design Review - GSFC		PM	4 mos ADC	8/17/93		not applicable			8/19/93	n/a	n/a	n/a	
230		5.2.2	Critical Design Review - Darnes		PM	7 months ADC	11/16/93		not applicable			11/17/93	n/a	n/a	n/a	
230		5.2.3	Pre-Test Review - Darnes		PM	1 month prior to test	9/27/94		not applicable			9/28/94	1153-138	n/a	n/a	
230		5.2.4	Pre-Ship Review - Darnes		PM	1 week prior to ship	11/24/94	/ /	not applicable			6/19/95	verbal	n/a	n/a	conducted at Darnes
240		5.2	PDR Data Package	R10	PM	2 wks prior PDR	8/ 3/93		none			9/04/93	1153-18	review	n/a	
240		5.2	CDR Data Package	R10	PM	2 wks prior CDR	11/ 2/93		none		11/11/93	11/11/93	1153-46	review	n/a	
250		5.2	PDR Report	A10	PM	2 wks after PDR	9/ 2/93		none			9/23/93	1153-26	07/27/94		
250		5.2	CDR Report	A10	PM	2 wks after CDR	12/ 2/93		none		1/13/94	1/14/94	1153-53	07/27/94		
260		7.1.1	Verification Test Plan	A-5	QC	2 wks prior PDR	8/ 3/93		QAPP-1153-002	A	AUG 93	8/17/93	1153-23	11/04/93	none	
260		7.1.1	Verification Test Plan	A-5	QC							3/ 6/95	1153-196	6/13/95	none	Change in sequence
270		7.1.2	Verification Test Procedures	A-5	QC	30 days prior to test			none - preliminary		8/31/94	8/31/94	1153-125	6/19/95		
270		7.1.2	Verification Test Procedures	A-5	QC	30 days prior to test			none		12/ 7/94	12/ 7/94	1153-152	6/19/95		
270		7.1.2	Verification Test Procedures	A-5	QC	30 days prior to test					3/ 3/95	3/ 3/95	1153-189	6/19/95		Has exception to 30 Days
270		7.1.2	Verification Test Procedures	A-5	QC	30 days prior to test			none	C	6/14/95	6/14/95	1153-247	6/19/95		
280		7.1	Verification Test Report	I-5	QC	30 days after test completion	/ /				/ /	/ /		info	n/a	
290		10.0	Verification Test Data Package	A-3	QC	with Hardwdre	12/01/94	/ /	none		6/28/95	6/28/95	1153-263	/ /		
300		10.0	Performance Assurance Status Rpt	R-5	QC	part of Monthly Status Report	n/a		not separately issud		/ /	/ /		n/a	n/a	
310		10.0	Product Changes	R-3	QC	As generated	as req	/ /			/ /	/ /		review	n/a	
320		10.0	Certificate of Inspection & Test	R-5	QC	One month after matl receipt	/ /	/ /			/ /	/ /		review	n/a	
330		10.0	Fastener Certification	R-3	QC	One month after receipt of ord	/ /	/ /			/ /	/ /		review	n/a	
340		10.0	Fastener Screening & Test Data	R-3	QC	One month after test complete	/ /	/ /			/ /	/ /		review	n/a	
350		10.0	Fabrication & Assembly Flow Plan	R-3	MfEng	2 wks prior CDR	11/02/93		QFC-1153-001	A	11/04/93	11/10/93	1153-43	review	n/a	
360		10.0	Malf. Failure Rpt - Notice/Oral	I-1	QC	Orally within 24 hours	as req				/ /	/ /		info	n/a	All closed
360		10.0	Malf. Failure Rpt - Notice/Written	R-3	QC	with 3 working days	as req				/ /	/ /		review	n/a	All closed
360		10.0	Malf. Failure Rpt - Analysis/Corr	R-5	QC	As generated	as req				/ /	/ /		review	n/a	All closed
360		10.0	Malf. Failure Rpt - Close-Out Rpt	A-5	QC	As generated	as req				/ /	/ /		5/19/95		All closed
370		10.0	Alerts	I-3	Rel	As generated	as req				/ /	/ /		info	n/a	
380		10.0	Test Coupons (1/board)	R-1	QC	30 days prior to use						4/15/94	1153-71	review	n/a	
380		10.0	Test Coupons (1/board)	R-1	QC	30 days prior to use						4/20/94	1153-73			
380		10.0	Test Coupons (1/board)	R-1	QC	30 days prior to use						5/04/94	1153-77	review	n/a	
380		10.0	Test Coupons (1/board)	R-1	QC	30 days prior to use						6/14/94	1153-93			
380		10.0	Test Coupons (1/Board)	R-1	QC	30 days prior to use						6/20/94	1153-90			
380		10.0	Test Coupons (1/Board)	R-1	QC	30 days prior to use						9/ 9/94	1153-127			Substitute Test Coupon
380		10.0	Test Coupons (1/board)	R-1	QC	30 days prior to use					10/ 3/94	10/ 3/94	1153-134			
390		10.0	Test/Inspection Procedures	R-5	QC	30 days prior to use	/ /	/ /			/ /	/ /		review	n/a	
400		10.0	Handling/Storage/etc.Procedures	A-2	QC	60 days prior to use	/ /	/ /			5/19/95	5/19/95	1153-257	5/19/95		
410		10.0	Waiver Request	A-2	PM	As generated	as req				/ /	/ /		/ /		
410		10.0	Deviation Request	A-2		As generated	as req		D-1153-001		7/19/94	7/19/94	1153-109	09/27/94	none	also apprvd 10/24/94
410		10.0	Deviation Request	A-2		As generated	as req		D-1153-002		8/01/94	8/02/94	1153-112	11/17/94	none	resubmitted as Rev. 0 3/16/95
410		10.0	Deviation Request	A-2		As generated	as req		D-1153-002	0	3/15/95	3/15/95	1153-194	3/16/95	none	
410		10.0	Deviation Request	A-2		As generated	as req		D-1153-003		8/03/94	8/03/94	1153-115	10/24/94	none	
410		10.0	Deviation Request	A-2		As generated	as req		D-1153-003 clarify		8/09/94	8/09/94	1153-116	10/24/94	none	
410		10.0	Deviation Request	A-2		As generated	as req		D-1153-003		9/19/94	9/19/94	1153-130	10/24/94	none	
410		10.0	Deviation Request	A-2		As generated	as req		D-1153-004		8/18/94	8/19/94	1153-120	11/17/94	none	awaiting No. 0 Test Results
410		10.0	Deviation Request	A-2		As generated	as req		D-1153-004		4/25/95	4/25/95	1153-217	4/21/95	none	also submitted on 3/15/95
410		10.0	Deviation Request	A-2		As generated	as req		D-1153-005		8/17/94	8/17/94	1153-119	10/24/94	none	

ITEM NO	REFERENCE CONTR	SOW	TITLE DESCRIPTION	CATEGORY & QTY	COG. DEPT	CONDITION	CONTRACT DUE DATE	CURRENT ESTIMATE	BARNES DELIVERABLE ACTIVITY REPORT NUMBER	REV	DATED	SENT	SERIAL	DATE NASA/GSFC APPROVED	APPROVAL LETTER SERIAL	COMMENTS
41B		10.0	Deviation Request	A-2		As generated	as req		D-1153-006		8/17/94	8/17/94	1153-119	10/24/94	none	
41B		10.0	Deviation Request	A-2		As generated	as req		D-1153-007		9/23/94	9/23/94	1153-122	11/17/94	none	
41B		10.0	Deviation Request	A-2		As generated	as req		D-1153-008		12/ 9/94	12/ 9/94	1153-155	1/23/95	none	1153-256 - closed at Barnes
41B		10.0	Deviation Request	A-2		As generated	as req		D-1153-009		2/ 9/95	2/ 8/95	1153-170	3/19/95		
41B		10.0	Deviation Request	A-2		As generated	as req		D-1153-010		2/ 9/95	2/ 9/95	1153-171	n/a		Replaced by D-1153-010, Rev. A
41B		10.0	Deviation Request	A-2		As generated	as req		D-1153-010	A	3/ 3/95	3/ 3/95	1153-186A			Replaced by D-1153-010, Rev. B
41B		10.0	Deviation Request	A-2		As generated	as req		D-1153-010	B	3/ 8/95	3/ 8/95	1153-190	3/19/95		
41B		10.0	Deviation Request	A-2		As generated	as req		D-1153-011		3/ 9/95	3/ 9/95	1153-192	3/19/95		App. w/ comments
41B		10.0	Deviation Request	A-2		As generated	as req		D-1153-012		3/10/95	3/10/95	1153-193	3/19/95		App. w/ condition
41B		10.0	Deviation Request	A-2		As generated	as req		D-1153-013	A	4/19/95	4/19/95	1153-214	4/25/95		
41B		10.0	Deviation Request	A-2		As generated	as req		D-1153-014		4/25/95	4/25/95	1153-218	4/29/95		
41B		10.0	Deviation Request	A-2		As generated	as req		D-1153-015		6/ 7/95	6/ 9/95	1153-237	6/13/95		
41B		10.0	Deviation Request	A-2		As generated	as req		D-1153-016		6/ 9/95	6/ 9/95	1153-239	6/13/95		
41B		10.0	Deviation Request	A-2		As generated	as req		D-1153-017		6/13/95	6/13/95	1153-245	6/13/95		
42B	C.2		Final Report	A-5	PM	30 days after delivery of H/W	1/ 1/95	/ /	none		7/19/95	7/19/95	1153-264			
5B		4.1	Interface Control Document (Final)	419	PM				none		12/ 7/94	12/ 7/94	1153-151	5/19/95		req apprvl by 12/15/94
C			==================================			.	99									
C			ADMINSTRATIVE REPORTS			.	99		-		/ /	/ /				
C			==================================			.	99				/ /	/ /				
1Ca			NASA New Technology Report (Intern)	I-1		Contr per 18-52.227-70	4/14/94	/ /	none		6/14/94	6/14/94	1153-94	info	n/a	Sent to GSFC Ch Patent Counsel
1Cb			NASA New Technology Report (Final)	I-1		Contr 18-52.227-70/3 mos after compl	2/28/95	/ /	none		7/ 5/95	7/ 5/95	1153-256	info	n/a	
2Ca	H.1c		SF-294 Subcontract Plan (20,3093)	I-2		Purch semi-annual	10/30/93		none		10/29/93	10/29/93	1153-42	info	n/a	
2Ca	H.1c		SF-294 Subcontract Plan (4093,1094)	I-2		Purch semi-annual	4/30/94	/ /	none		4/21/94	4/21/94	1153-74	info	n/a	
2Ca	H.1c		SF-294 Subcontract Plan (20,3094)	I-2		Purch semi-annual	10/30/94	/ /	none		10/31/94	10/31/94	1153-142	info	n/a	
2Ca	H.1c		SF-294 Subcontract Plan (4094)	I-2		Purch Final	4/30/95	/ /	none		4/12/95	4/12/95	1153-208	info	n/a	
2Cb	H.14		SF-295 Subcontract Report (2093)	I-2		Purch Quarterly	7/30/93		none			8/17/93	1153-24	info	n/a	
2Cb	H.14		SF-295 Subcontract Report (3093)	I-2		Purch Quarterly	10/30/93		none			10/29/93	1153-41	info	n/a	
2Cb	H.14		SF-295 Subcontract Report (4093)	I-2		Purch Quarterly	1/30/94		none			5/17/94	1153-84	info	n/a	
2Cb	H.14		SF-295 Subcontract Report (1094)	I-2		Purch Quarterly	4/30/94		none			5/17/94	1153-84	info	n/a	
2Cb	H.14		SF-295 Subcontract Report (2094)	I-2		Purch Quarterly	7/30/94		none		10/31/94	10/31/94	1153-141	info	n/a	
2Cb	H.14		SF-295 Subcontract Report (3094)	I-2		Purch Quarterly	10/30/94		none		10/31/94	10/31/94	1153-141	info	n/a	
2Cb	H.14		SF-295 Subcontract Report (4094)	I-2		Purch Quarterly	1/30/95		none		3/ 7/95	3/ 7/95	1153-188	info	n/a	
2Cb	H.14		SF-295 Subcontract Report (1095)	I-2		Purch Quarterly	4/30/95		none		4/13/95	4/13/95	1153-209	info	n/a	
2Cb	H.14		SF-295 Subcontract Report (2095)	I-2		Purch Quarterly	7/30/95									
3C	I.11		NASA Form 667 - Subcontracts	I-x		Purch w/i 10 days after execution	/ /	/ /			/ /	/ /		info	n/a	Negative Reports Required
4C	E.7		DD Form 250	I-2	QC	with hardware deliveries	6/01/94	/ /			5/18/95	5/18/95		5/18/95	n/a	
4C	E.7		DD Form 250	I-2	QC	with hardware deliveries	12/01/94				6/22/95	6/22/95		6/22/95	n/a	
I			==================================			.	99									
I			NON - CDRL DELIVERABLES			.	99									
.			==================================			.	99									
70	B.3c		Request for Additional Funding	I-1		Contr 50 days prior period end	10/31/93		no request required		n/a	n/a	n/a	n/a	n/a	Funding received
70	B.3c		Request for Additional Funding	I-1		Contr 60 days prior period end	2/15/94		none		2/14/94	2/14/94	1153-61	info	n/a	
71	C.2		NASA Form 1626 Report Doc. Page	1	PM	with EACH submitted report	as req									Ref: NASA FAR 18-52.235-70
71	C.2		SF 298 Report Documentation Page	1	PM	in ALL docs sent to NASA CASI	as req									
72	G.3		SF 1443 Prog Payment #1 - Apr 93	A-3	Accts	Accts Ref: NASA FAR 18-52.232-82	5/15/93		INVOICE 32154		5/12/93	5/13/93	1153-04	paid		
72	G.3		SF-1443 Prog Payment #2 - May 93	A-3	Accts		6/15/93		INVOICE 32202		6/15/93	6/18/93	1153-08	paid		
72	G.3		SF-1443 Prog Payment #3 - Jun 93	A-3	Accts		7/15/93		INVOICE 32252		7/22/93	7/22/93	1153-17	paid		
72	G.3		SF-1443 Prog Payment #4 - Jul 93	A-3	Accts		8/15/93		INVOICE 32297		8/18/93	8/18/93	1153-25	paid		
72	G.3		SF-1443 Prog Payment #5 - Aug 93	A-3	Accts		9/15/93		INVOICE 32344		9/14/93	9/15/93	1153-31	paid		
72	G.3		SF-1443 Prog Payment #6 - Sep 93	A-3	Accts		10/15/93		INVOICE 32406		10/21/93	10/25/93	1153-39	paid		

ITEM NO	REFERENCE CONTR	SOW	TITLE DESCRIPTION	CATEGORY & QTY	COG. DEPT	CONDITION	CONTRACT DUE DATE	CURRENT ESTIMATE	BARNES DELIVERABLE ACTIVITY: REPORT NUMBER	REV	DATED	SENT	SERIAL	DATE NASA/GSFC APPROVED	APPROVAL LETTER SERIAL	COMMENTS
72	6.3		SF-1443 Prog Payment #7 - Oct 93	A-3	Acctg		11/15/93		INVOICE 32447		11/15/93	11/22/93	1153-48	paid		
72	6.3		SF-1443 Prog Payment #8 - Nov 93	A-3	Acctg		12/15/93		INVOICE 32525		12/29/93	12/30/93	1153-52	paid		
72	6.3		SF-1443 Prog Payment #9 - Dec 93	A-3	Acctg		1/15/94		INVOICE 32575		2/04/94	2/04/94	1153-59	paid		
72	6.3		SF-1443 Prog Payment - Jan 94	A-3	Acctg		2/15/94		not submitted							
72	6.3		SF-1443 Prog Payment - Feb 94	A-3	Acctg		3/15/94		not submitted							
72	6.3		SF-1443 Prog Payment - Mar 94	A-3	Acctg		4/15/94		not submitted							
72	6.3		SF-1443 Prog Payment #10 - Apr 94	A-3	Acctg		5/15/94		INVOICE 32694		5/16/94	5/19/94	1153-85	paid		
72	6.3		SF-1443 Prog Payment #11 - May 94	A-3	Acctg		6/15/94		INVOICE 32750		6/16/94	6/16/94	1153-95	paid		
72	6.3		SF-1443 Prog Payment #12 - Jun 94	A-3	Acctg		7/15/94		INVOICE 32812		7/12/94	7/26/94	1153-111	paid		
72	6.3		SF-1443 Prog Payment #13 - Jul 94	A-3	Acctg		9/15/94		INVOICE 32958		8/17/94	8/22/94	1153-121	paid		
72	6.3		SF-1443 Prog Payment #14 - Aug 94	A-3	Acctg		9/15/94		INVOICE 32905		9/22/94	9/22/94	1153-132	paid		
72	6.3		SF-1443 Prog Payment #15 - Sep 94	A-3	Acctg		10/15/94		INVOICE 32932		10/12/94	10/12/94	1153-138	paid		
72	6.3		SF-1443 Prog Payment #16 - Oct 94	A-3	Acctg		11/15/94		INVOICE 32993		11/11/94	11/11/94	1153-146	paid		
72	6.3		SF-1443 Prog Payment #17 - Nov 94	A-3	Acctg		12/15/94		INVOICE 33019		12/ 7/94	12/ 7/94	1153-154	paid		
72	6.3		SF-1443 Prog Payment #18 - Dec 94	A-3	Acctg		01/15/95		INVOICE 33067		1/15/95	1/15/95	1153-163	paid	3/29/95	Payment was $ 50 short
72	6.3		SF-1443 Prog Payment #19 - Jan 94	A-3	Acctg		2/15/95		INVOICE 33119		2/29/95	2/28/95	1153-181	paid		Payment was $ 441 short
72	6.3		SF-1443 Prog Payment #20 - Feb 95	A-3	Acctg		3/15/95		INVOICE 33149		3/20/95	3/20/95	1153-198	paid		Payment was $ 277 short
72	6.3		SF-1443 Prog Payment #21 - Mar 95	A-3	Acctg		4/15/95		INVOICE 33176		4/14/95	4/14/95	1153-211	paid		Payment was $2,731 short
72	6.3		SF-1443 Prog Payment #22 - Apr 95	A-3	Acctg		5/15/95		INVOICE 33213		5/12/95	5/12/95	1153-225			Final submittal/may not b paid
72	6.3		DD Form 250 Final Payment - Jun 95	A-3	Acctg		6/15/95		INVOICE 33254		6/27/95	6/27/95	1153-265			
73	6.4		Request for Electronic Funds Trans.		Acctg req. Amend to Contract		as req				/ /	/ /				
94	M.2		Agenda - PDR	I-2	PM	2 wks prior PDR	9/03/93		none			9/10/93	1153-20	info	n/a	
94	M.2		Agenda - CDR	I-2	PM	2 wks prior CDR	11/02/93		none			11/17/93	none	info	n/a	
84	M.2		Agenda - Pre-Test	I-2	PM	2 wks prior Pre-Test	/ /94		none		9/23/94	/ /		info	n/a	Completed
84	M.2		Agenda - Pre-Ship Review	I-2	PM	2 wks prior Pre-Ship	11/17/94	/ /	none		6/19/95	6/19/95	verbal	info	n/a	via telephone.
85	M.2		Minutes - PDR	I-2	PM	at conclusion of PDR	8/19/93		none			8/23/93	1153-26	info	n/a	
85	M.2		Minutes - CDR	I-2	PM	at conclusion of CDR	11/18/93		none		1/13/94	1/14/94	1153-53	info	n/a	
85	M.2		Minutes - Pre-Test Review	I-2	PM	at conclusion of Pre-Test	/ /94	10/18/94	none		9/23/94	/ /		info	n/a	Completed
85	M.2		Minutes - Pre-Ship Review	I-2	PM	at conclusion of Pre-Ship	11/23/94	/ /	none		6/19/95	6/19/95		info	n/a	
96	I.9		Notification of Changes		Contr w/i 30 days...FAR 52.243-7		as req	/ /			/ /	/ /				
97	I.13		Key Personnel		PM		as req		Elsendorf for Tobin		6/ 5/95	6/ 5/95	1153-230	6/ 7/95	n/a	
99	I.14		Engineering Change Proposals		Contr if submitted		as req	/ /			/ /	/ /				NASA FAR 18-52.243-79
94			Polymeric Materials List (Prelim)	R-3	Rel	30 days prior PDR	7/19/93		none			9/10/93	1153-29			ref: PAR: 6.2.5
94			Polymeric Materials List (Final)	A-3	Rel	30 days prior CDR			none	A	8/30/93	11/10/93	1153-43			ref: PAR: 6.2.5
94			Polymeric Materials List (Updates)	A-3	Rel	As Generated										ref: PAR: 5.2.5
94			Polymeric Materials List (As Built)	I-3	Rel	With End-Item ADP										ref: PAR: 6.2.5
00																

APPENDIX B

DESIGN of OBJECTIVE LENS for TRMM

Design of Objective Lens

for

Tropical Rainfall Measurment Mission

Earth Sensor Assembly

(TRMM ESA)

Prepared By:

Rana Dutta
Static Sensor Systems

1. INTRODUCTION:

The objective lens for the Tropical Rainfall Measuring Mission ESA (TERESA) will have the same rear surface radius of curvature as the original DMSP ESA objective lens (i.e., R2=151.72mm); however, the first surface curvature, R1, will be 108.06*mm*, the center thickness of the lens will be increased to 5*mm* and the lens will have to provide a larger deviation angle of 10.43° to deviate the look down angle of the original DMSP ESA sensor to 73.03°. This deviation is required to accommodate the different altitudes and dip-ins between the DMSP and TERESA's. The deviation of the FOV is accomplished by wedging the objective lens by 3.39°.

2. DISCUSSION:

The lens design methodology for TERESA is based on the design of the objective lens for the MELCO program (see Reference 1 for a copy of MELCO lens design). This is because both the TERESA and the MELCO are DMSP-like ESA's having lower operational altitudes than DMSP. The effect of having a lower operational altitude is the earth nadir angle or look down angle is larger, i.e., the earth's horizon is larger in angular subtense than for the standard ESA and the static sensor's fields-of-view is not positioned on the earth's horizon. The method in which this can be corrected with the minimal amount of change to the original design is to modify the objective lens so that it increases the nadir or look down angle to that for TERESA.

2.1 *Design Requirements:*

The TRMM sensor must be able to measure pitch and roll over a ±1° attitude range with an accuracy of ±0.08°±7% for a 335*Km* to 365*Km* operational altitude range (350*Km* is the nominal altitude). There is an additional requirement for operation over an altitude range of 200*Km* to 400*Km*, but with degraded accuracy and attitude range.

2.2 *Nadir Angle Calculation:*

The first step in determining the new look down angle for TERESA is to determine what the nadir angles are in the standard ESA and TERESA. Given, the altitude above the hard earth (*ALT*), the earth's radius (for simplicity we will assume the earth is not an oblate spheroid and use the earth's equatorial radius, *REQ*), and the average height of the earth's CO_2 atmosphere (*HCO2*), the earth's horizon angle (or half of the earth's angular subtense) can be found by:

$$\Phi(ALT) = Sin^{-1}\left(\frac{REQ + HCO2}{REQ + ALT}\right) \tag{2.2.1}$$

where:

$$REQ = 6371Km \qquad \& \qquad HCO2 = 40Km$$

In the design for the MELCO lens, the altitude used for the standard DMSP was 833.33Km which would have a horizon angle of:

$$\Phi(833.33Km) = 62.86° \tag{2.2.2}$$

However, the nadir or look down angle, which is defined as "the angle between the optical axis of the ESA's B field-of-view and the yaw axis of the satellite", is 62.6° in the standard DMSP style ESA. This would correspond to a nominal altitude of 850Km instead of 833.33Km. The difference of 0.26° in the look down angle has the effect of increasing the nominal dip-in from 2.6° to 2.86°. For the DMSP, MARS and MELCO programs this caused no measurable performance degradation but, since there is no reason for this discrepancy, the TERESA design will not propagate the dip-in angle difference. So, for the calculation of the nadir angle change, we will assume the nominal altitude of the DMSP is 850Km, which produces the following horizon angle:

$$\Phi(850Km) = 62.60° \tag{2.2.3}$$

Next, applying equation (2.2.1) for the TRMM nominal altitude of 350*Km*:

$$\Phi(350Km) = 72.53° \tag{2.2.4}$$

Then, the change in look down angle required due to the different operational altitude is:

$$\Delta\Theta = \Phi(350Km) - \Phi(850Km) = 9.93° \tag{2.2.5}$$

This look down angle change provides the same nominal dip-in as the standard ESA which is 2.6° assuming an 850Km nominal altitude. A 2.6° dip-in means that at the nominal altitude (of 850*Km* for DMSP) at a null attitude position (Pitch = 0 & Roll = 0), the earth's horizon covers half of the B field-of-view. Additionally, if the altitude were not to change, the range over which the attitude could vary

would be around ±2.6°. However, since the altitude varies from 740*Km* to 925*Km*, the operational attitude range is reduced to ±1°.
On TRMM, the altitude varies from 200*Km* to 400*Km*, which in terms of the earth's horizon angle is a variation of 77.33° to 71.23°. That translates to approximately a 6° variation in the earth's horizon. In addition, if a ±1° attitude range is to be provided over this altitude range, a total of 8° would be required of the B FOV. However, since the detector is only capable of covering a 5.2° field space range, it may be advantageous to select a dip-in other than 2.6° which will provide coverage over a reduced altitude range that will be most useful to TERESA's needs within the 5.2° field space. The dip-in chosen was 2.1° which provides coverage all the way to the highest altitude of 400*Km*, but with reduced operational attitude range (around ±0.4° in pitch and roll at 400*Km*). The reason the attitude range is limited at 400*Km* is because the detector becomes very noisy with smaller dip-ins and the smaller dip-in is a result of the earth's horizon becoming smaller as the altitude becomes larger (see Figure 1). If the attitude were allowed to vary the full ±0.8° at 400*Km*, the error due to noise would be severe at the furthest attitude positions. Therefore, approximately 0.2° of the B FOV is left for noise margin. A more detailed description of the noise is available in the system error analysis document for TERESA.

The 2.1° dip-in does have the advantage of providing ±1° attitude range to an altitude down to 285*Km*. This is illustrated in Figure 1, which shows the location of the earth's horizon at null for a number of altitudes. As can be seen in Figure 1, as the altitude decreases, the earth's horizon increases covering more and more of the B FOV. At 285*Km*, the earth's horizon is located about 4° into the B FOV, leaving the remaining 1.2° of the B FOV for attitude range and error margin. Attitude information will be available for the region between 285Km to 200Km, but by a different method. The two methods that have presently been considered are to let the altitude decrease until the earth's horizon begins to illuminate the S FOV or to pitch or roll the unit 1° to 2° and use the sensor in a two detector operational mode. Both options will have degraded performance, however, the latter method will avoid the potential of a dead band. These options have been described in more detail in earlier correspondence with NASA Goddard (see Appendix 1, memos RD20-93 and RD21-93).

A reduced dip-in also has the advantage of reducing the error due to radiance variations at null. Since the accuracy required by the TRMM sensor is 0.08° ± 7% of the true attitude range, while the original ESA was 0.1°, the smaller dip-in will help in reducing the radiance error at null.

On the other hand, a smaller dip-in has the effect of increasing the noise errors. And so, from a noise standpoint, a larger dip-in is more desirable. Therefore, the choice of the dip-in was made by trading off the errors that were dependent on the dip-in and the optimal location was found to be 2.1°.

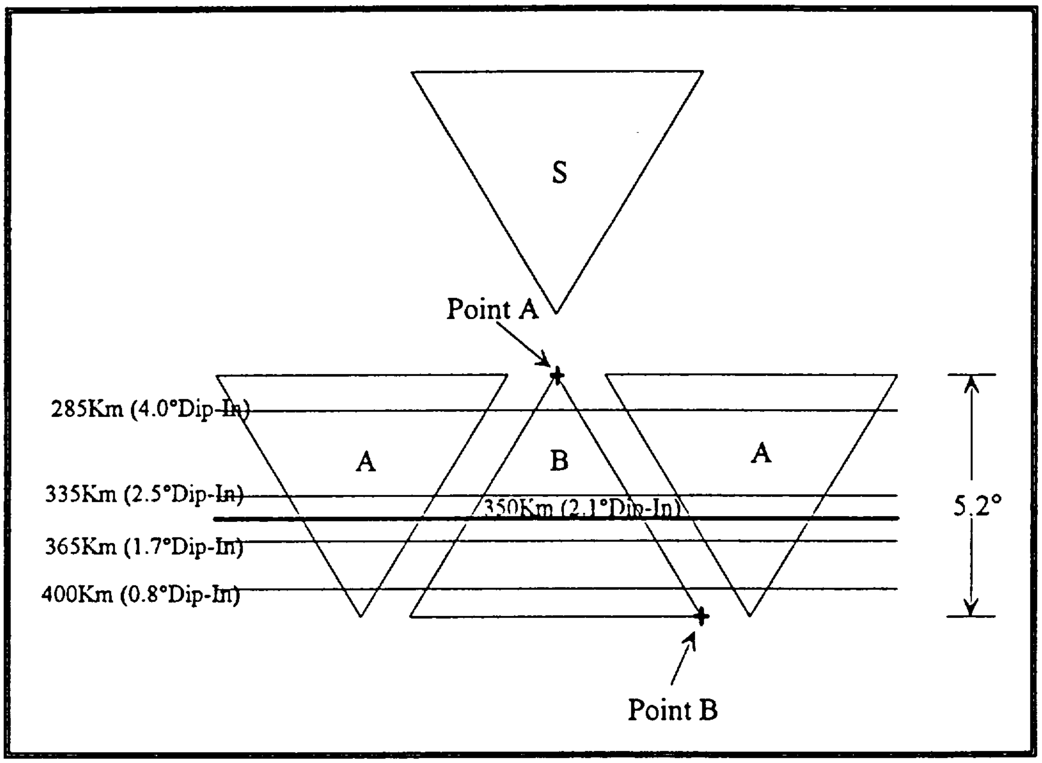


Figure 1 - Earth Horizon Positions on the Detector FOV vs. Altitude

Going back to the look down angle calculation, a dip-in change from 2.6° to 2.1° will result in an additional change in the look down angle of:

$$\Delta\Theta_1 = 2.6° - 2.1° = 0.5° \tag{2.2.6}$$

Therefore, the look down angle required for TERESA, which accounts for the new altitude range and the different nominal dip-in, will be the original look down angle of the standard ESA (Θ_{ESA} = 62.6°) plus the change in angle,$\Delta\Theta$ plus the dip-in difference ($\Delta\Theta$ = 0.5°). See Figure 2 for an illustration of the nadir angle definitions for the standard ESA, MARS, MELCO, and TERESA.

$$\Theta_{TRMM} = \Theta_{ESA} + \Delta\Theta + \Delta\Theta_1 = 62.6° + 9.93° + 0.5° = 73.03° \tag{2.2.7}$$

And the change in the look down angle is:

$$\Delta\Theta + \Delta\Theta_1 = 9.93° + 0.5° = 10.43° \qquad (2.2.8)$$

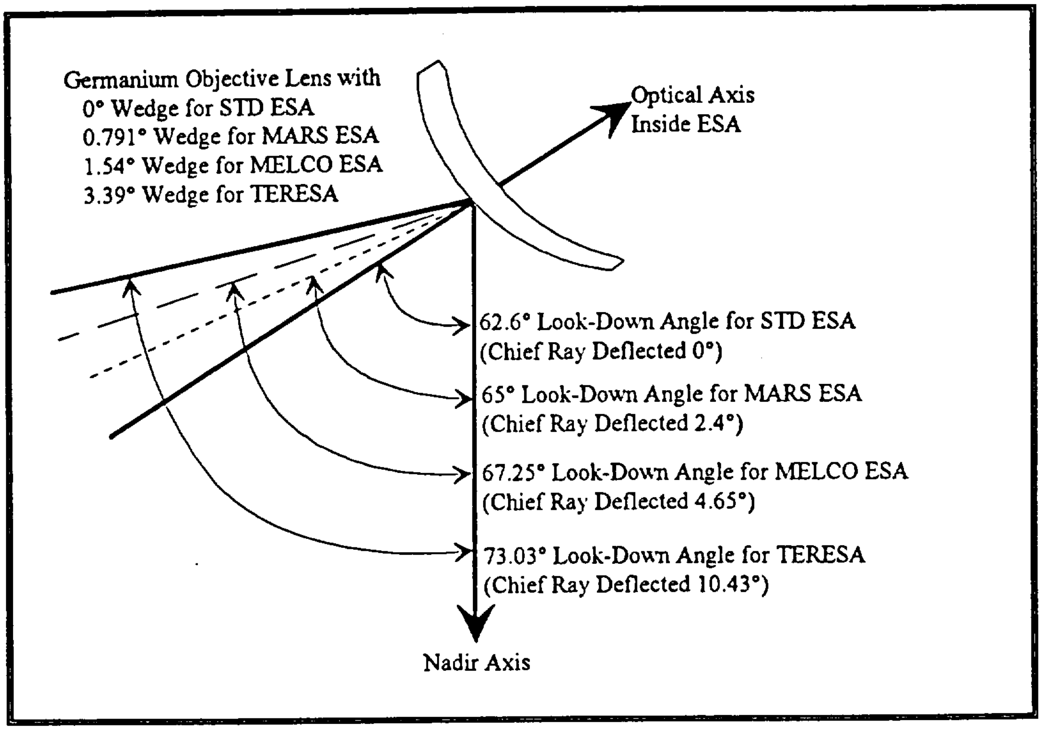


Figure 2 - Look Down Angle Requirements for Various ESA Sensors

2.3 *Wedge Angle Calculation:*

So, having found the objective lens must deviate the FOV by 10.43°, the next step is to determine what the wedge angle must be. Referring to my memorandum RD17-93, "Prism Formulas for Non-Minimum Deviation", included in Appendix 1, we can estimate the approximate wedge angle, α, that will be required. This approximate calculation can be used as a starting point and refined by an optical raytrace analysis using Code V.

$$\alpha = Tan^{-1}\left[\frac{\frac{1}{4.002} Sin(10.43°)}{\sqrt{1 - \frac{1}{4.002} Sin^2(10.43°)} - \frac{1}{4.002}}\right] = 3.46° \qquad (2.3.1)$$

Equation (2.3.1) is the calculation for the apex or wedge angle of a non minimum deviation prism in terms of the index of refraction, n=4.002 (which is the index of refraction of germanium in the 14μm to 16μm bandwidth at 25°C), and the deviation angle, i=10.43°.

This apex angle of 3.46° is then used only as a starting point for the lens design. Using Code V, the optimal wedge angle was found to be 3.39°. The reason there is a difference between the apex angle calculated by equation 2.1 and the optimal wedge angle is that the apex angle calculated by the equation is the exact solution for a prism whose front and back surfaces do not have curvature. For TERESA, the two surfaces of the prism do not have zero curvature and therefore, the true apex angle for a wedged lens is slightly different than that for a simple prism.

2.4 *Lens Design Objectives:*

As in the MELCO lens design, the main objective is to minimize the amount of redesign to the standard ESA optical head. In doing so, the fixed parameters of the design are the radius of curvature for the rear surface of the lens. This is so the ORS mirror can be mated to the rear surface of the lens without any change to the mirror. The axis of the rear surface will also be kept the same with respect to the axes of the field lenses. Another fixed parameter is the back focal length of the optical system. The back focal length is the distance from the objective lens to the field lens and it must be kept the same as the standard ESA to avoid mechanical changes to the optical head. And the final fixed parameter that has just been defined is the wedge angle of the lens which is 3.39°.

Given these fixed parameters, the variables are the thickness of the lens and the curvature of the front surface. Since the wedge angle of the lens has increased significantly, it will be necessary to increase the center thickness of the lens so that the edge thickness is not too small (edge thickness should not be less than 1mm). We will try 5mm for the center thickness of the lens and verify that it will provide adequate thickness at the edge. Then, as a baseline we will assume the same radius of curvature for the front surface of the lens as in MELCO. This initial curvature is 106.71mm and it will be optimized to improve the image quality or spot size of the point images at the top and bottom edges of the B field-of-view (these points are shown as Point A and Point B in Figure 1).

2.5 *Lens Front Surface Curvature Calculations:*

Having defined the wedge of the lens to be 3.39°, and the center thickness to be 5mm, the last remaining variable in the lens design is the curvature of the front surface of the lens. Again, Code V will be used to optimize the lens front surface curvature. A layout of the optical model is shown in Figure 3. The layout only shows the optics to the field lens, i.e., the field lens and the cone optics are not included. The reason for this is because the field lens and mirrored cone are only used to collect the energy from the aperture stop and flood it onto the detector. An obscuration has been included in the center of the objective lens to model the location of the ORS mirror in the actual optical system. The listing for the lens system is shown in Listing 1.

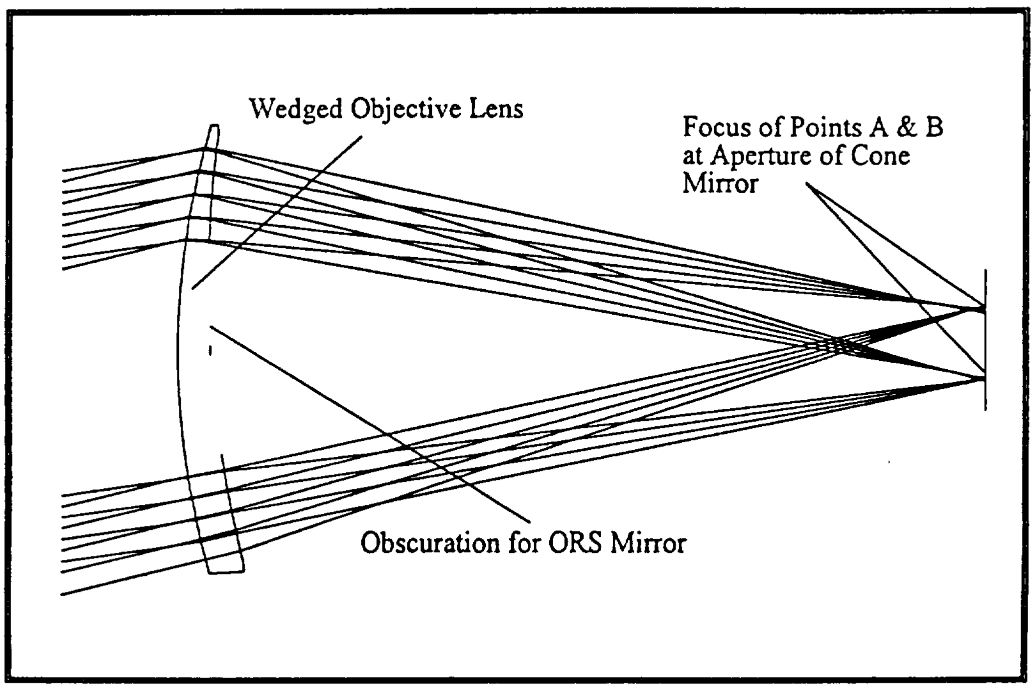


Figure 3 - TERESA Optical Layout

Using Code V's AUTO design feature, the curvature was adjusted to minimize the tangential blur of the spots for the two field angles at the ends of the detector - points A and B in Figure 1. All other parameters except the radius of curvature for the front surface was held constant. After the optimization, the final curvature was 108.06*mm*.

2.6 *Lens Thickness Calculations:*

In the design of this 3.39° wedged objective lens it is desirable from a fabrication standpoint to ensure the edge thickness of the lens is not too small. The general practice has been to design the lens such that the minimum edge thickness is not less than 1*mm*. However, another design objective is to design the lens for greatest optical throughput, and that is achieved by designing the lens to be as thin as possible. Given these two opposing requirements, let us determine whether a 5*mm* center thickness provides an adequate edge thickness for the objective lens. The following discussion shows how to find the edge thickness of a wedged lens given the radii of curvature (*RDY1* & *RDY2*), the center thickness (*THI*), the wedge or apex angle (*ADE*), and the edge heights of the lens ($y1$ and $y2$).

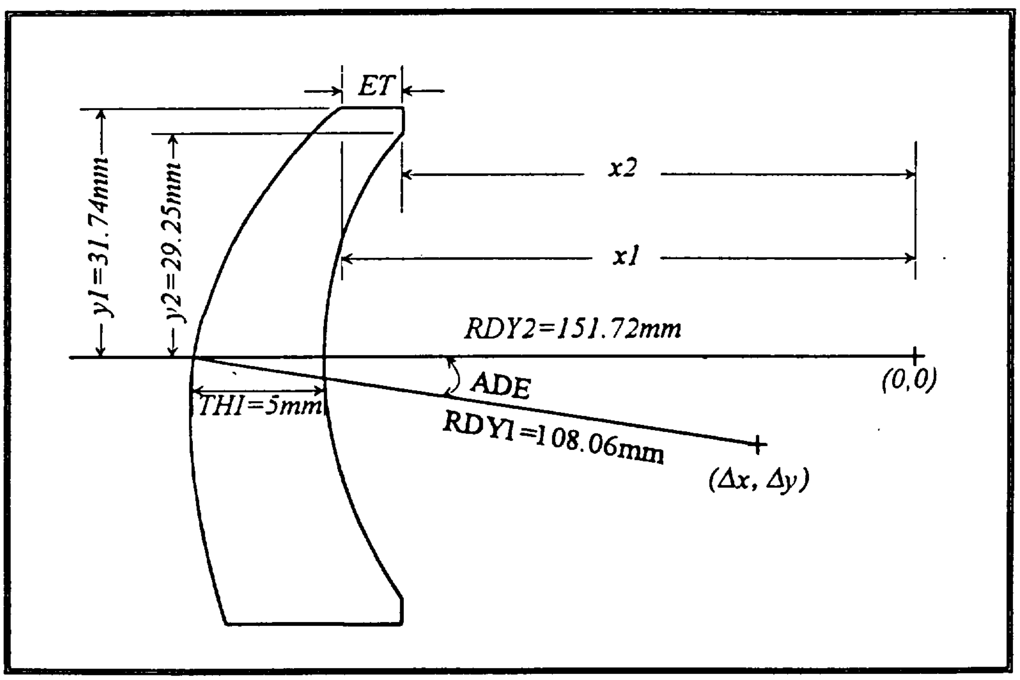


Figure 4 - Wedged Lens Diagram

Referring to Figure 4, the edge thickness (*ET*) is given by:

$$ET = x1 - x2 \tag{2.6.1}$$

The length $x1$ can be found by solving the equation of a circle centered at ($\Delta x, \Delta y$) with a radius of curvature *RDY1* and at a height of $y1$:

$$x1 = \sqrt{RDY1^2 - (y1 - \Delta y)^2} + \Delta x \tag{2.6.2}$$

Then, Δx and Δy are given by:

$$\begin{aligned} \Delta x &= RDY1 + THI - RDY2 \cdot Cos(ADE) \\ \Delta y &= -RDY1 \cdot Sin(ADE) \end{aligned} \tag{2.6.3}$$

And finally, $x2$ is found by solving the equation of a circle centered at the origin with radius of curvature $RDY2$ and at a height of $y2$:

$$x2 = \sqrt{RDY2^2 - y2^2} \tag{2.6.4}$$

Now, in the case of TERESA, the known variables are:

$RDY1$=108.06*mm*
$RDY2$=151.72*mm*
THI=5*mm*
ADE=3.39°
$y1$=31.74*mm*
$y2$=29.25*mm*

Substituting into equations (2.6.2), (2.6.3), & (2.6.4):

Δx=48.85*mm*
Δy=-6.39*mm*
x1=149.96*mm*
x2=148.87*mm*

And, finally, substituting into equation (2.6.1):

ET = 1.09*mm*

which is greater than the minimum requirement of 1*mm*. Therefore a center thickness of 5*mm* will provide enough edge thickness. As far as the throughput goes, there will be a small throughput loss; however, the loss is not expected to be large enough to degrade the overall performance of the optical system. To definitively quantify the optical loss, a transmission measurement would have to be made of this proposed lens and compared to the throughput of the MELCO lens, which is known to have had adequate optical throughput.

If the heights were negated (i.e., let y1=-31.74*mm* and y2=-29.25*mm*), the edge thickness for the thick side of the lens could be found using the same equations defined above. Making the substitution, the thick edge thickness is:

$ET_{thick\ side}$ = 5.02*mm*

2.7 *Evaluation of Optical Performance:*

The performance of this optical design is dependent primarily on the tangential blur size of spots that correspond to the field angles of points A and B in Figure 1. By looking at the spot diagram of Figure 5, it can be seen that the 100% tangential blur of Points A and B are 0.37° and 0.64°, respectively.

These blurs were calculated by measuring the tangential blur in physical space dimensions of millimeters and converting to angles using the factor 1.88*mm/°*. This factor was determined by tracing the chief ray of a number of different field angles from 8° to 14° in 1° increments and seeing where the chief ray intersected the image plane. The results of this calculation are shown in Table I. Figure 6 shows a plot of this field angle versus image position calculation and it shows that the transfer function is fairly linear over the field-of-view of the B detector.

Going back to Figure 5, notice that the blurs are 0.37° for Point A and 0.64° for Point B. Table II shows a comparison of the tangential blurs from the original ESA, the MELCO ESA and the proposed TERESA optics. It is apparent that the blurs are larger for the TERESA system than the previous ESA's; however, there is still no degradation in the performance of the system. This is because the field lenses due not form an image of the earth's horizon, but rather, just gathers the energy from the aperture stop and floods the entire detector. As long as the depression angle of the horizon at the highest altitude is large enough, aberrations will not affect the linearity of the transfer function.

Input Field Angle (YAN°)	Chief Ray Height (mm)	Displacement of Spot Centroid from Chief Ray (mm)	Image Height (mm)	Slope (mm/°)
8.00	-4.34	-0.24	-4.58	1.90
8.33	-3.72	-0.24	-3.96	1.90
9.00	-2.45	-0.24	-2.69	1.89
10.00	-0.56	-0.23	-0.80	1.89
10.43	0.25	-0.23	0.01	1.88
11.00	1.32	-0.23	1.09	1.88
12.00	3.19	-0.22	2.97	1.87
13.00	5.05	-0.21	4.84	1.88
13.53	6.04	-0.20	5.84	1.87
14.00	6.91	-0.20	6.72	
Average Slope				1.88

Table I - Image Height vs. Field Angle

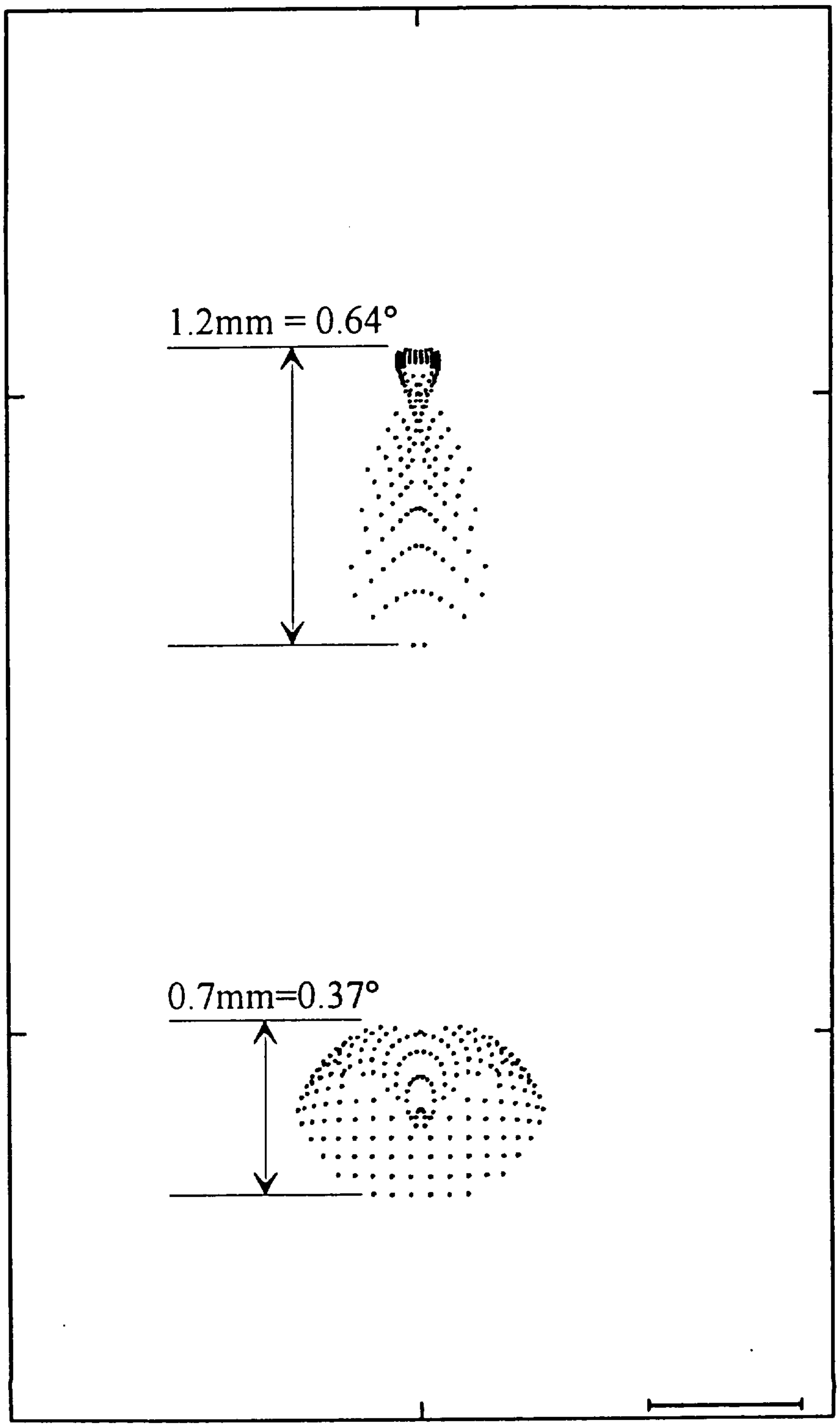


Figure 5 - Spot Diagrams for Points A & B

Field Position	Tangential Blur		
	Standard ESA	MELCO ESA	TERESA
Point A (Bottom Edge of B FOV)	0.14°	0.26°	0.37°
Point B (Top of B FOV)	0.17°	0.30°	0.64°

Table II - Comparison of Tangential Blur from Previous ESA's

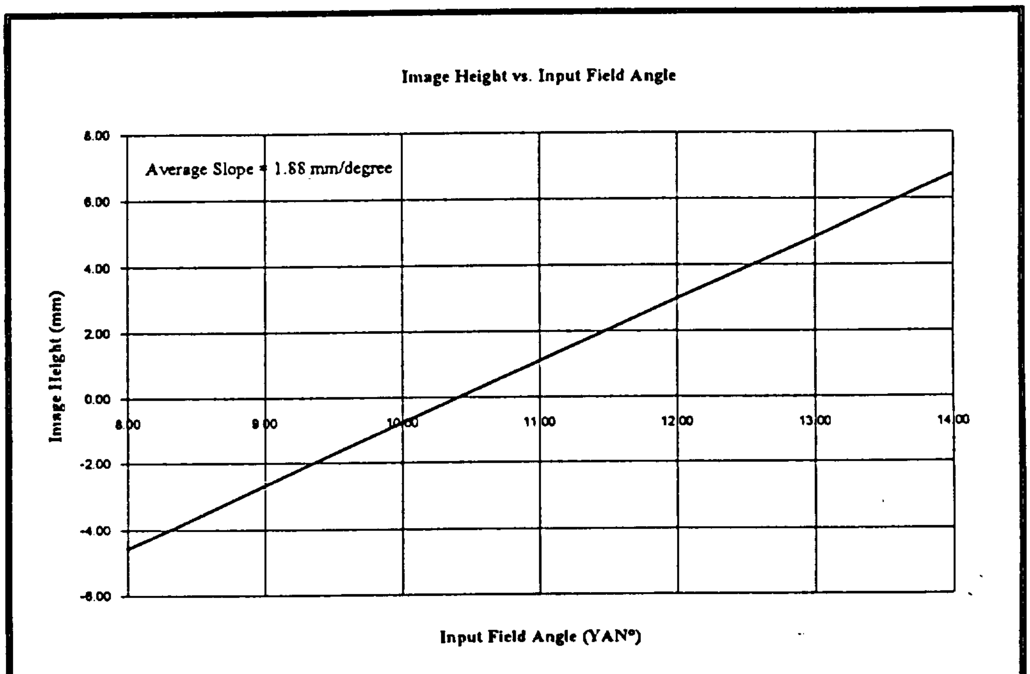


Figure 6 - Image Position vs. Field Angle Plot

To calculate the minimum depression angle, Θ_{min}, that can be allowed, let's assume that the minimum depression angle must be at least half of the 100% blur width at the bottom edge of the B FOV. So,

$$\Theta_{min} = \frac{0.37^\circ}{2} = 0.185^\circ$$

Since we have imposed a minimum depression angle of 0.25°, which is .085° greater than the minimum depression angle allowed because of the blur, there will be adequate signal from the blur spot and the transfer function will be linear.

2.8 *Temperature Effects on Wedged Lens:*

A major concern in designing wedged objective lenses is the effects due to temperature changes. When the temperature of the lens changes, the lens' index or refraction changes causing the deviation angle to change. This change in deviation angle may cause a significant pointing bias if the temperature difference from one of the objective lenses is very different from the other lenses (remember that this sensor consists of four wedged objective lenses to view the four quadrants of the earth).

Based on input from a thermal analysis of the spacecraft, the temperature difference on one of the lenses with respect to the others is 5°C. For germanium, the optical material of these lenses, the temperature coefficient, *dn/dT*, is:

$$\frac{dn}{dT} = 4 \times 10^{-4}/°C \qquad \text{or} \qquad \Delta n = (4 \times 10^{-4}) \cdot \Delta T \tag{2.8.1}$$

Since $\Delta T = 5°C$, Δn is:

$$\Delta n = \pm 0.002$$

The nominal index of refraction for germanium at 25°C is:

$$n = 4.002$$

So, the index change for a ±5°C temperature change is:

$$n_{max} = 4.004$$
$$n_{min} = 4.000$$

Now, given the wedge or apex angle, α, of the lens along with the index of refraction, *n*, of the germanium lens, the deviation angle, *i*, can be found by (see RD17-93 memo for the origin of this formula):

$$i = Sin^{-1}\left\{n \cdot Sin\left[\alpha - Sin^{-1}\left(\tfrac{1}{n} \cdot Sin(\alpha)\right)\right]\right\} \tag{2.8.2}$$

Since the apex angle has been fixed to 3.39° and the nominal index is 4.002, the nominal deviation angle should be:

$$i_{nom} = 10.230°$$

Notice that this does not agree exactly with the actual nominal deviation angle of 10.43°, but again, that is because we are using a formula for simple prisms that do not have curvatures. Nonetheless, this formula can be used because we are only interested in the change in deviation angles with change in index and using the prism formulas for a difference calculation would agree closely for the wedged objective lens. Then, using the maximum and minimum indices of refraction with the deviation angle equation, the maximum and minimum deviation angles are:

$$i_{max} = 10.236°$$
$$i_{min} = 10.223°$$

Therefore, the error in the depression angle due to a single lens becoming 5°C warmer or cooler than the other lenses will be ±0.007°. The error in pointing due to this depression angle error is given by (the derivation of this can be found in the noise analysis document):

$$\Delta P4 = \tfrac{\sqrt{2}}{4}(\Delta x_2 - \Delta x_4 + \Delta x_3 - \Delta x_1) \tag{2.8.3}$$

$$\Delta R4 = \tfrac{\sqrt{2}}{4}(\Delta x_2 - \Delta x_3 + \Delta x_4 - \Delta x_1) \tag{2.8.4}$$

Now, since there is a bias in only one of the depression angles, the overall pointing error will be:

$$\Delta P4 = \Delta R4 = \tfrac{\sqrt{2}}{4} \cdot \Delta x = 0.0025°$$

This would be the resultant worst error in both pitch and roll, but the worst error in just pitch or just roll would occur if two of the fields changed temperature by 5°C. Then the maximum attitude error would be:

$$\Delta P4 = \tfrac{\sqrt{2}}{4} \cdot (2 \times \Delta x) = 0.005° \quad \& \qquad \Delta R4 = 0$$

or

$$\Delta R4 = \tfrac{\sqrt{2}}{4} \cdot (2 \times \Delta x) = 0.005° \quad \& \qquad \Delta P4 = 0$$

depending on which two lenses see the temperature change. In any event, whether the combined pitch and roll error or the single axis attitude error is concerned, the effect due to temperature change is small enough to be unmeasureable by the sensor and so may be neglected.

LISTING 1

Code V Listing of TRMM Objective Lens

```
CODE V> lis
     TRMM Objective Lens
                RDY                   THI       RMD         GLA           CCY    THC    GLC
  OBJ:        INFINITY              INFINITY                              100    100
    1:       108.06083              5.000000          'ge'                  0    100
      XDE:    0.000000   YDE:     0.000000   ZDE:      0.000000   DAR
      XDC:     100       YDC:      100       ZDC:       100
      ADE:   -3.390000   BDE:     0.000000   CDE:      0.000000
      ADC:     100       BDC:      100       CDC:       100

 > STO:      151.72000              0.000000                              100    100
    3:        INFINITY            106.740000                              100    100
  IMG:        INFINITY              0.000000                              100    100

 SPECIFICATION DATA
    EPD       60.00000
    DIM             MM
    WL        15000.00
    REF              1
    WTW              1
    XAN        0.00000
    YAN       10.43000
    VUX        0.00000
    VLX        0.00000
    VUY        0.00000
    VLY        0.00000

 APERTURE DATA/EDGE DEFINITIONS
    CA
    CIR S1                      29.250000
    CIR S2                      29.250000
    CIR S2   OBS                14.625000
    CIR S1   EDG                31.735000
    CIR S2   EDG                31.735000

 PRIVATE CATALOG
    PWL            15000.00
    'ge'           4.002000

    PWL            15000.00
    'ge10c'        3.996300

 REFRACTIVE INDICES
     GLASS CODE                      15000.00
    'ge'                             4.002000

 No solves defined in system

        This is a decentered system.  If elements with power are
        decentered or tilted, the first order properties are probably
        inadequate in describing the system characteristics.

 INFINITE CONJUGATES
    EFL        115.1947
    BFL        111.1964
    FFL       -118.0423
    FNO          1.9199
    IMG DIS    106.7400
    OAL          5.0000
    PARAXIAL IMAGE
     HT         28.7213
    ANG         14.0000
    ENTRANCE PUPIL
     DIA        60.0000
     THI         1.2943
    EXIT PUPIL
     DIA        57.9175
     THI         0.0000
CODE V> out t
```

APPENDIX 1

To:	M. Conley
cc:	J. Shepherd
From:	R. Dutta
Date:	April 27, 1993
Subject:	Prism Formulas for Non-Minimum Deviation (RD17-93)

This discussion presents the derivation of the apex angle or wedge angle of a non-minimum deviation prism required for a given deviation angle. Figure 1, below illustrates the relevant variables for the derivation.

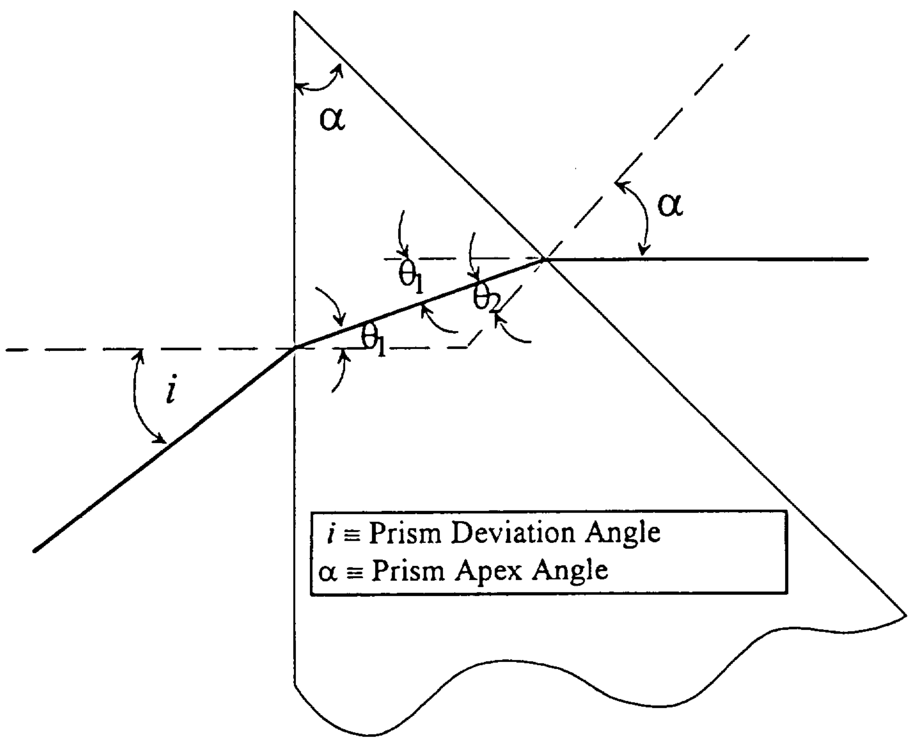


Figure 1 - Non-Minimum Deviation Prism Diagram

-The first equation that can be derived using Snell's Law is:

$$Sin(i) = nSin(\theta_1) \quad \text{or} \quad Sin(\theta_1) = \tfrac{1}{n} Sin(i) \tag{1}$$

Again, using Snell's Law:

$$nSin(\theta_2) = Sin(\alpha) \tag{2}$$

Referring to Figure 1, it can seen that:

$$\theta_2 = \alpha - \theta_1 \tag{3}$$

So, substituting (3) into (2):

$$\begin{aligned}
&nSin(\alpha - \theta_1) = Sin(\alpha)\\
&Sin(\alpha)Cos(\theta_1) - Cos(\alpha)Sin(\theta_1) = \tfrac{1}{n}Sin(\alpha)\\
&Cos(\theta_1) - \frac{Sin(\theta_1)}{Tan(\alpha)} = \frac{1}{n}\\
&Tan(\alpha) = \frac{Sin(\theta_1)}{Cos(\theta_1) - \frac{1}{n}(9)}
\end{aligned} \tag{4}$$

Now, using the trigonometric identity:

$$Cos(\theta_1) = \sqrt{1 - Sin^2(\theta_1)} \tag{5}$$

Equation (4), combined with equations (1) and (5) can be written as:

$$\boxed{\alpha = Tan^{-1}\left[\frac{\frac{1}{n}Sin(i)}{\sqrt{1 - \frac{1}{n^2}Sin^2(i)} - \frac{1}{n}}\right]} \tag{6}$$

Which expresses the apex angle, α, in terms of the deviation angle, i, and the index of refraction, n.

In addition, we can solve for the deviation angle, i, as function of the apex angle, α, and the index of refraction of the material, n.

$$\boxed{i = Sin^{-1}\left\{n\,Sin\left[\alpha - Sin^{-1}\left(\tfrac{1}{n}Sin(\alpha)\right)\right]\right\}} \tag{7}$$

Rana Dutta

R. Dutta - Static Sensor Systems

To:	M. Conley
cc:	NASA Goddard TRMM Team
From:	R. Dutta
Date:	May 25, 1993
Subject:	Extended Range Capabilities of Standard ESA (RD20-93)

The standard ESA configuration in based on an array of four detectors arranged around the horizon of the earth with a nominal dip-in of 2.6°. That is to say, that when the sensor was at its nominal altitude of 833Km and at a null position, the penetration or depression angle, x, as shown in Figure 1, of the A and B fields would all be the same and equal to 2.6°. Each detector array consists of four triangular fields - two A fields, one B field and an S field. The two A fields are averaged together and are used to provide a measure of the radiance in the vicinity of the B field. The B field combined with the A fields are used to determine the amount penetration, x, into the earth and the penetration from each of the four detector arrays is used to determine the pitch and roll attitude.

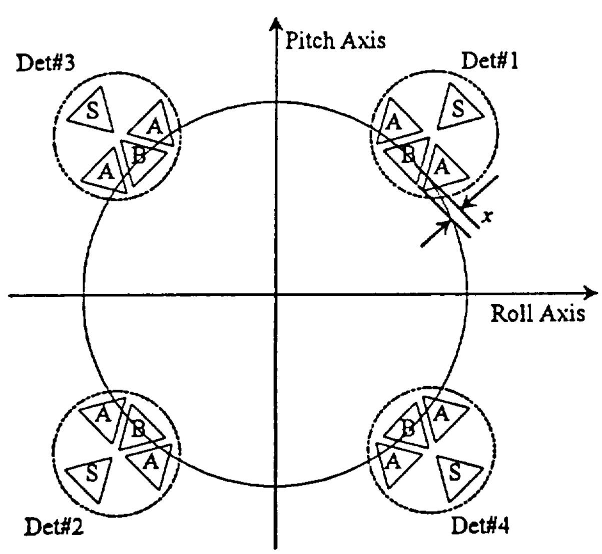


Figure 1 - Detector Orientation for an Earth Sensor Assembly

The A, B and S fields are 5.2° high, and so, the total range of operation available from the sensor is 5.2 (actually, it is somewhat less than 5.2° because of the angular jitter which increases at the ends of the fields-of-view), which has to provide for attitude changes as well as altitude changes. The altitude for the standard ESA ranges from 740Km to 925Km which results in an angular earth radius varying from 64.4° to 61.5°. As the altitude of the satellite increases, the apparent angular subtense of the earth tends to decrease, and likewise, as the altitude decreases, the angular subtense of the earth increases. This has the effect of causing greater nominal dip-ins as the altitude decreases and smaller nominal dip-ins as the altitude increases. So, the altitude variation requires a total of 64.4°-61.5°= 2.9° of the 5.2° FOV. In addition, the attitude range is ±1°. So an additional 2° is required in the FOV for a total of 4.9°. The remaining 0.3° is not used since the angular jitter error becomes large at the ends of the FOV.

Now for the TRMM mission, the altitude range varies from 200Km to 400Km, which has an angular earth subtense variation from 77.3° to 71.2° or 6.1°. In addition, if we wished to provide a ±1° attitude variation range, another 2° would be needed for a total field-of-view of 8.1°. Since the FOV of the ESA is 5.2° and the required FOV for TRMM is 8.1°, there will have to be some compromises made to achieve the extended altitude range.

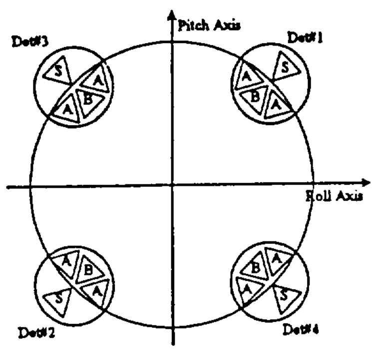


Figure 2 - Detectors Fully Illuminated by Earth for Low Altitudes

The altitude region in which the highest accuracy is required maintaining ±1° of attitude range is 335Km to 365Km. If the optics is optimized for this region, there will be larger penetration angles, *x*, for altitudes below 335Km, i.e., the apparent earth horizon will become larger at lower altitudes. As the altitude is decreased even further, the earth's angular subtense will increase until, eventually, all the B fields will be filled by the earth's horizon. This is shown in Figure 2. Then, for about 1°, which is the gap between the B field and S field, the sensor will not be able to show attitude changes until the altitude is reduced further and information can be obtained but, with degraded accuracy that has not yet been determined.

There is a way in which the attitude can be evaluated without a dead band, i.e., a way to provide change in attitude information for the full range of an altitudes. This can be accomplished by pitching or rolling the sensor 1° or 2° so that two of the detectors are not fully dipped-into the earth's horizon. In this way, two of the detectors can show changes in depression angles for changes in attitude. This is illustrated in Figure 3. Figure 3 shows the condition in which the altitude is decreased to the point that if the sensor were positioned at null, all the A and B fields would be fully illuminated by the earth. By pitching the sensor, detector arrays 1 and 4 can detect attitude changes ensuring that a dead band does not occur.

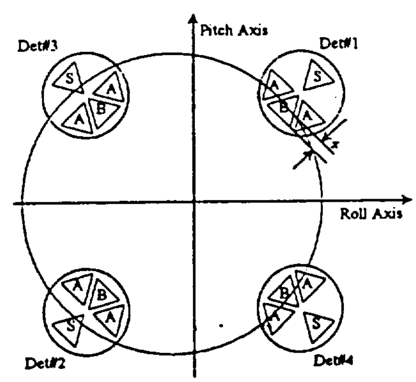


Figure 3 - Pitched Detector Orientation

R. Dutta - Static Sensor Systems

To:	M. Conley
cc:	NASA Goddard TRMM Team
From:	R. Dutta
Date:	May 25, 1993
Subject:	Operational Range Trade-Offs for TRMM ESA (RD21-93)

The existing TRMM specification requires a 0.08°±7% accuracy over an attitude range of ±1° and over an altitude range of 350Km±15Km. In addition, the specification requires that there be some performance over a 200Km to 400Km altitude range, but with degraded accuracy. Some compromises will have to be made in the performance of the ESA over the 200Km to 400Km altitude range. This is because the field-of-view of the sensor spans only 5°. Achieving high accuracy over the 200Km to 400Km altitude range combined with the ±1° attitude range would require a field-of-view that spans 8°. This is discussed in more detail in my memo RD20-93.

With additional information from the customer, the required compromises can be made in a way that will optimize the ESA for TRMM's on-orbit operation.

Before listing the various trade-offs and compromises, let me first outline my understanding of the system requirements in order of importance to the mission.

1) The sensor must, as a minimum, provide ±1° attitude range from 335Km to 365Km with a 0.08°±7% accuracy.

2) The satellite may overshoot and be injected into an orbit with a 400Km altitude, but the satellite will then be reset to the 350Km±15Km altitude range.

3) The satellite needs to be controlled during reentry, and that is why there is a 200Km altitude requirement.

Now, based on these three requirements, it would be helpful to also know:

a) Is there need for ±1° attitude range in the region from 365Km to 400Km? A smaller attitude range (say ±0.25°) would provide greater altitude range at the lower altitudes with all four detectors viewing the earth's horizon.

b) For the region below 335Km, does the sensor have to operate at null or can it operate pitched or rolled by 1° or 2°? The purpose for pitching or rolling a fixed amount is to ensure there is no dead band at the lower altitudes. If the unit is pitched or rolled a fixed amount, then the attitude can be determined using two of the detector's fields.

c) Again, is ±1° attitude range required below 335Km or can some reduced attitude range be accommodated? A smaller attitude range can provide for a larger altitude range with four field operation.

d) Will the typical attitude maneuvers be a combined pitch and roll maneuver or will it be fixed along the pitch axis or roll axis? This is important to know because it may be possible to provide greater attitude range along a fixed axis rather than combined pitch and roll.

Finally, let me suggest that a dip-in of 2.1° be selected and that 2-detector operation be used where appropriate. In this case I estimate the "degraded performance" achievable over the 200Km to 400Km altitude range to be as below.

Altitude Range	Attitude Range	Operating Mode	Expected Error (ε)
200Km to 284Km	1°±0.5°	2-Detector	$0.15° < \varepsilon < 0.3°$
285Km to 334Km	±1°	4-Detector	$0.15° < \varepsilon < 0.3°$
335Km to 365Km	±1°	4-Detector	0.08°±7%
366Km to 385Km	±1°	4-Detector	$0.1° < \varepsilon < 0.25°$
386Km to 400Km	±0.25°	4-Detector	$0.1° < \varepsilon < 0.25°$

This configuration also has the advantage of easy adoption to other operating altitudes (say 370Km±15Km), should this be necessary.

Rama Dutta

R. Dutta - Static Sensor Systems

REFERENCE 1

Design of Objective Lens for ERS-1 Program (MELCO)

MEMORANDUM

DATE: March 13, 1987

TO: R. Bates

FROM: R. Gontin

SUBJECT: Design of Objective Lens for ERS-1 Program (MELCO)

INTRODUCTION:

This memo summarizes the final design of the objective lens that will be used in the ESA static sensor for the ERS-1 program of MELCO. It describes the objective lens as well as key points in the design process.

REQUIREMENTS:

MELCO requires a static sensor to measure the attitude (pitch and roll) of their ERS-1 satellite which will orbit the earth at a mean altitude of 568 km. Because the standard ESA manufactured by Barnes Engineering is designed to work at a nominal altitude of 833 km (450 nautical miles), its nadir angle (i.e. angle between nadir direction and center of the B FOV) would normally be too low for this mission. This would cause the A and B fields of view of the ESA to impinge too far into the image of the earth's horizon for proper operation. The nadir angle of the ESA must therefore be increased to allow the sensor to operate over the range of 568 $\pm$60 km required by the ERS-1 program.

Calculation of Nadir Angle of Sensor

To compute how much we must increase the nadir angle, first refer to Figure 1 and note that the standard ESA has a nadir angle of:

$$\theta = 62.6^{\circ}$$

Basic geometry provides the equation relating a sensor's altitude to the horizon angle:

$$\Phi(A) = \mathrm{Arcsin}\{(R_E + h_{co2})/(R_E + A)\}$$

where:

R_E ≡ mean radius of the earth = 6371 kilometers

A ≡ altitude of sensor = 568 kilometers

h_{co2} ≡ mean height of C02 horizon profile = 40 km

$\phi(A)$ ≡ horizon angle as a function of altitude

Although the C02 radiance profile has no precise altitude, 40 km, the altitude of its half radiance point, is usually taken as the value of h. Let the difference between the nadir angles corresponding to the standard ESA altitude (833 km) and the nominal altitude for ERS-1 (568 km) be $\Delta\theta$. Then from the equation for nadir angle:

$$\Delta\theta = \Phi(568 \text{ km}) - \Phi(833 \text{ km}) = 4.647^\circ$$

$$\Delta\theta = 4.647^\circ$$

This value of 4.647° is the angle by which we must increase the nadir angle of the standard ESA to make it compatible with the lower altitude of the ERS-1 mission. The final design value for the nadir angle is therefore:

$$\theta_{\text{ERS1}} = \theta_{\text{ESA}} + \Delta\theta$$

$$\theta_{\text{ERS1}} = 62.6^\circ + 4.647^\circ$$

$$\theta_{\text{ERS1}} = 67.247^\circ \cong 67.25^\circ$$

where:

θ ESA $\equiv$ nadir angle of the standard ESA = 62.6°

θ ERS1 $\equiv$ nadir angle of the sensor for ERS-1

$\Delta\theta$ $\equiv$ calculated increase in nadir angle = 4.647°

Here we define "nadir angle" as the angle between the optical axis of the ESA's "B" FOV and the yaw axis of the satellite.

OBJECTIVES OF THE DESIGN

To eliminate the need for major redesign of the ESA optical head, Barnes Engineering is using a wedge, or prismatic objective lens to accommodate the standard ESA sensor to the 67.25 degree nadir angle required for the ERS-1 sensor. So, except for the objective lens cell, no changes in the design of the ESA optical head will be needed. The main requirements of the design are as follows:

1. The objective lens must deflect the chief ray of the incoming parallel ray bundle by 4.65 degrees as shown in Figure 1. This changes the direction of the ESA's FOV from its normal 62.6 degrees to the 67.25 degrees required for ERS-1.

2. The rear, R2, surface of the lens must have the same radius of curvature as the standard ESA objective. The axis of this surface must also be unchanged with respect to the axes of the field lenses. This is important because the sensor design requires that the ORS mirror be bonded to the R_2 surface of the objective. By keeping the curvature of this surface the same as for the standard ESA objective (151.72 mm radius), the ORS mirror's mating surface will not need to be changed.

3. The thickness must be no less than 1.0 mm at any point on the edge of the lens. This will ensure enough mechanical strength for mounting the lens.

4. The back focal plane of the optical system must be the same as for the standard ESA. When the lens is installed into the ESA optical head, its focal plane must be at the back of the field lens of the B FOV, just as it is in the standard ESA. This is important since all distances and orientations of the field lenses with respect to the back surface of the objective will be the same in this optical system as it is in the standard ESA.

Besides these main requirements, Barnes Engineering sought to achieve two other goals in the design:

1. The design should be optimized to have its best image quality at the following two points in the triangular B FOV:

   a. upper apex of the triangle.

   b. lower corner of the triangle.

Figure 2 shows where these points are in the sensor's fields of view.

Image quality here means what is commonly called the spot size or "blur" diameter of a point image. We need good image quality at point a. to prevent the image of the horizon's edge from "spilling over" into the S FOV should the horizon ever be at its maximum limit into the field (near 5.2 degrees from the lower edge). Likewise, minimum blur at point b. will keep the transfer function linear for the cases of extremely small angles of horizon penetration (about 0.2 degrees). Note that image quality is relatively unimportant near the center of the field, at 2.6 degrees penetration, since the FOV merely gathers optical energy for the detector. The detector receives the same amount of optical flux from a blurred horizon edge as from a sharply imaged one whenever the horizon is not near the top or bottom limits of the triangular field.

2. The front surface of the objective should be spherical. By avoiding aspheric surfaces in the design, fabrication costs will be kept lower.

It is important to note that the wedge design does not change the angular size of the standard ESA triangular fields of view. They will remain 5.2° high in the sensor for ERS-1.

DESCRIPTION OF DESIGN

A copy of the optical data sheet attached to this memo describes the design in terms of the optical parameters needed for its fabrication. Figure 3 shows a ray diagram for the lens focused onto the field lens of the B FOV. Notice that:

1. The first surface is tilted 1.54 degrees with respect to the back surface. This is the wedge angle needed to deflect the chief ray of the system by the required 4.65 degrees.

2. The ray diagram shows an obscuration of 29.25 mm at the center of the lens that corresponds to where the ORS mirror will be fastened to the back of the lens. This is not specified on the data sheet because it is not important for manufacturing the objective. The obscuration was taken into account in the design, however, because it does affect the aberrations of the optical system.

The following is a summary of the first order parameters for this design:

Focal Length: 112.34 mm

Clear Aperture: 58.5 mm

Lens Material: Germanium

Index of Refraction: 3.9963 for 15 um wavelength at specified operating temperature of 10 C.

Radius of Curvature of Front Surface (R1): 106.71 mm (convex)

Radius of Curvature of Back Surface (R2): 151.72 mm (concave)

Thickness at Center of lens: 4.12 mm

Wedge Angle between Lens Surfaces: 1.54 degrees

EVALUATION OF OPTICAL PERFORMANCE

Figures 4 and 5 are optical spot diagrams of the image at points a. and b., which were described earlier. The table below compares the 100% tangential blur (in degrees) for this design to those for the standard ESA lens. The tangential blur, or blur measured in the direction perpendicular to the horizon's image is the important parameter here. Sagittal blur would not affect the system's performance since the horizon's image runs parallel to this direction.

FIELD POSITION	TANGENTIAL BLUR STANDARD ESA	TANGENTIAL BLUR ERS-1 SENSOR
Point a. (lower apex of B FOV)	0.14 deg.	0.26 deg
Point b. (upper apex of B FOV)	0.17 deg.	0.30 deg

These results show that adding the 1.54° wedge to the objective has almost doubled the width of the optical blur inside the B FOV. This will not affect the sensor's performance, however, because:

- As explained before, the field lenses do not form an image of the horizon, but merely gather energy for the detector. As long as the depression angle of the horizon (i.e. angle between the horizon and the lower edge of the B FOV) is great enough, aberrations will not affect the linearity of the transfer function at extreme attitudes or altitudes. To compute the minimum depression angle that can be allowed, we very conservatively assume that it must be at least half of the 100% blur width at the lower corner of the B FOV. So,

$$\theta_{min} = \frac{0.26^\circ}{2} = 0.13^\circ$$

where:

$\theta_{min} \equiv$ minimum allowable depression angle

This is much less than the minimum depression angle of 1.44°, which corresponds to the highest altitude of 628 km specified for the ERS-1 mission.

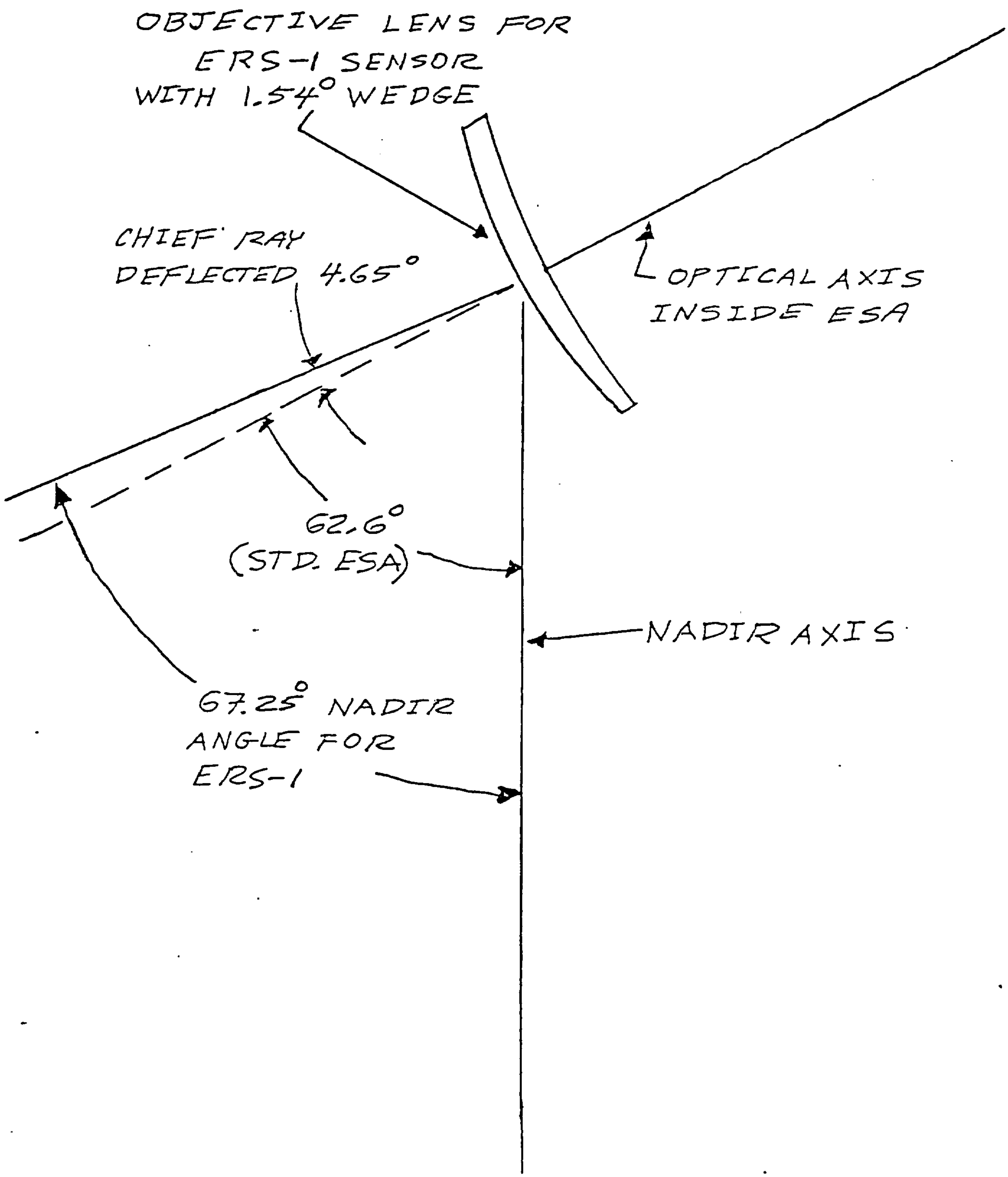
- The optical blur is still only a fraction of the uncertainty or "blur" that is always present in the earth's CO_2 radiance profile. Because the horizon's shape is really like a ramp subtending an angle of about 0.9° at 568 km, this blur is at least three times the width of the worst case optical blur. Any uncertainty in the image caused by optical aberrations will thus be negligible.

The design will therefore meet the requirements for ERS-1 mission by allowing the ESA sensor to operate a mean altitude of 568 km.

R.A. Gontin

FIGURE 1.

ORIENTATION OF OBJECTIVE RELATIVE TO NADIR



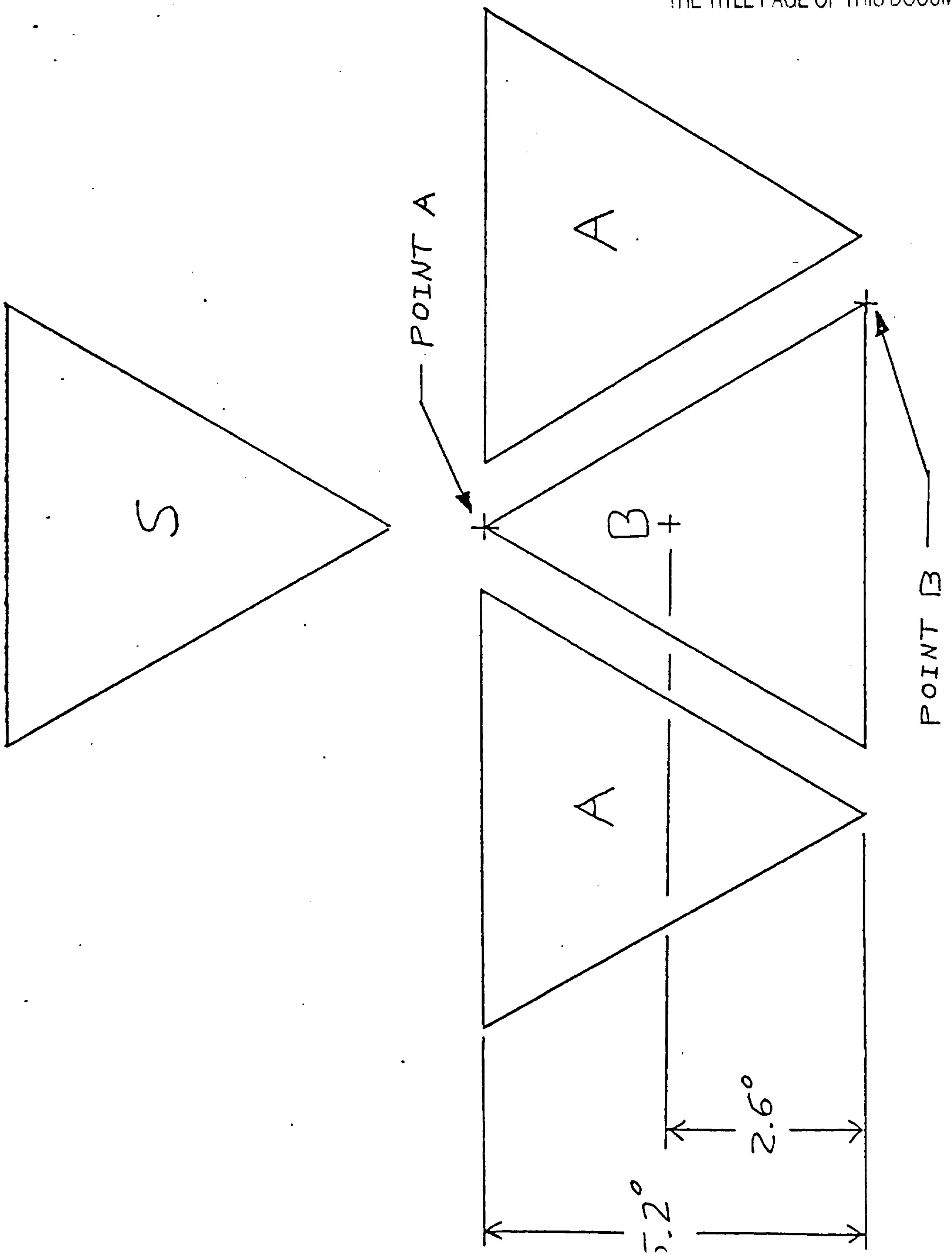


FIG. 2: ESA FIELDS OF VIEW

Date 03-17-1987 Time 13:52:36 File Name melsys5
4.12 mm thick - 106.24 mm spacing
Plot Limits (x-axis) -12.161   150   Y Offset 0

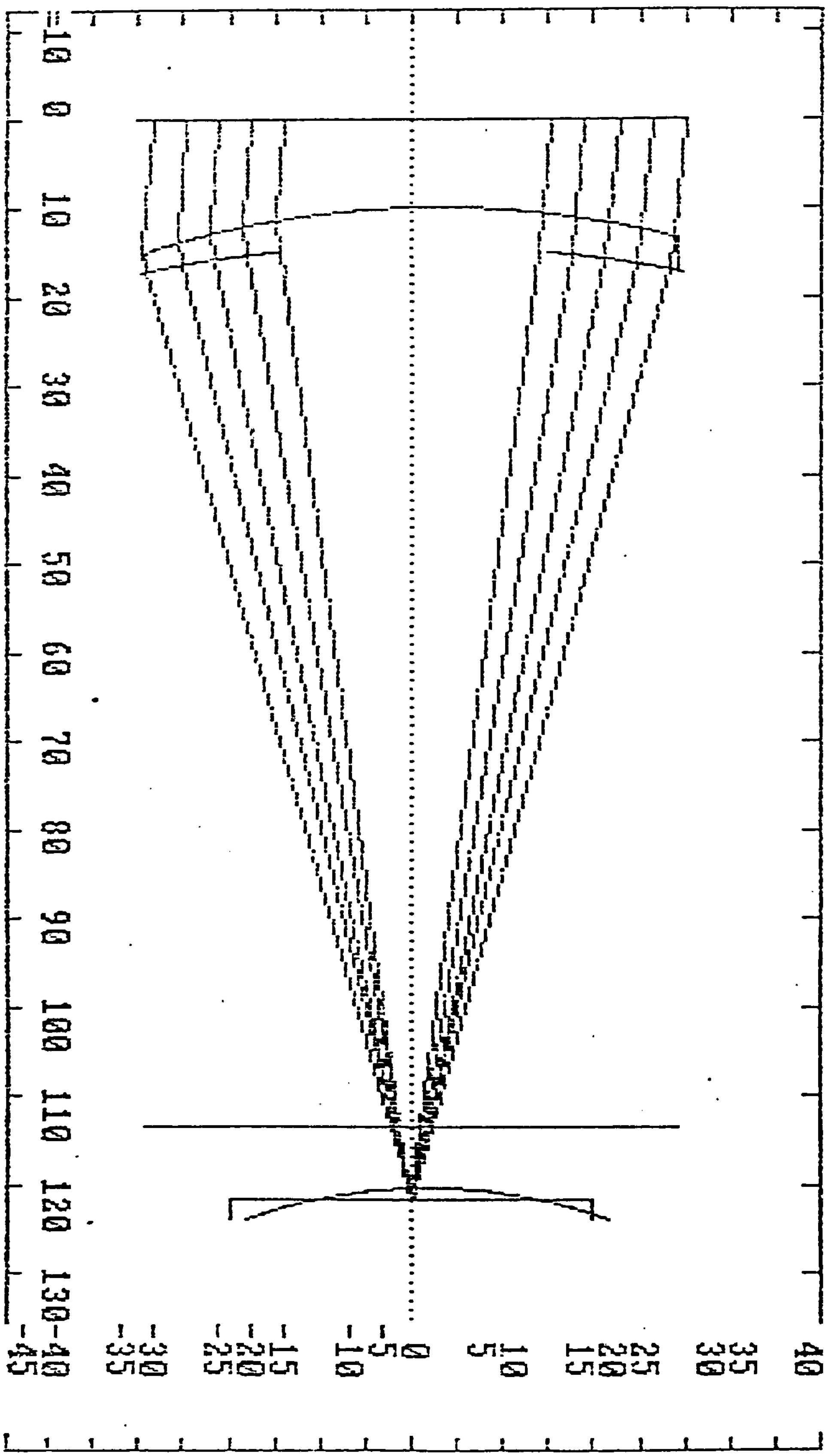


FIGURE 3

FIGURE 4

Data file name MELSYS5
Date 03-11-1987
Time 15:36:12
Wavelength 1
Image Plane   121.61
Field angles
  T-plane -2.05
  S-plane 0

limits Y direction
 6.000973
 4.000973
limits Z direction
 6.753478
 4.753478
Dimensions in mm
rays/color 100

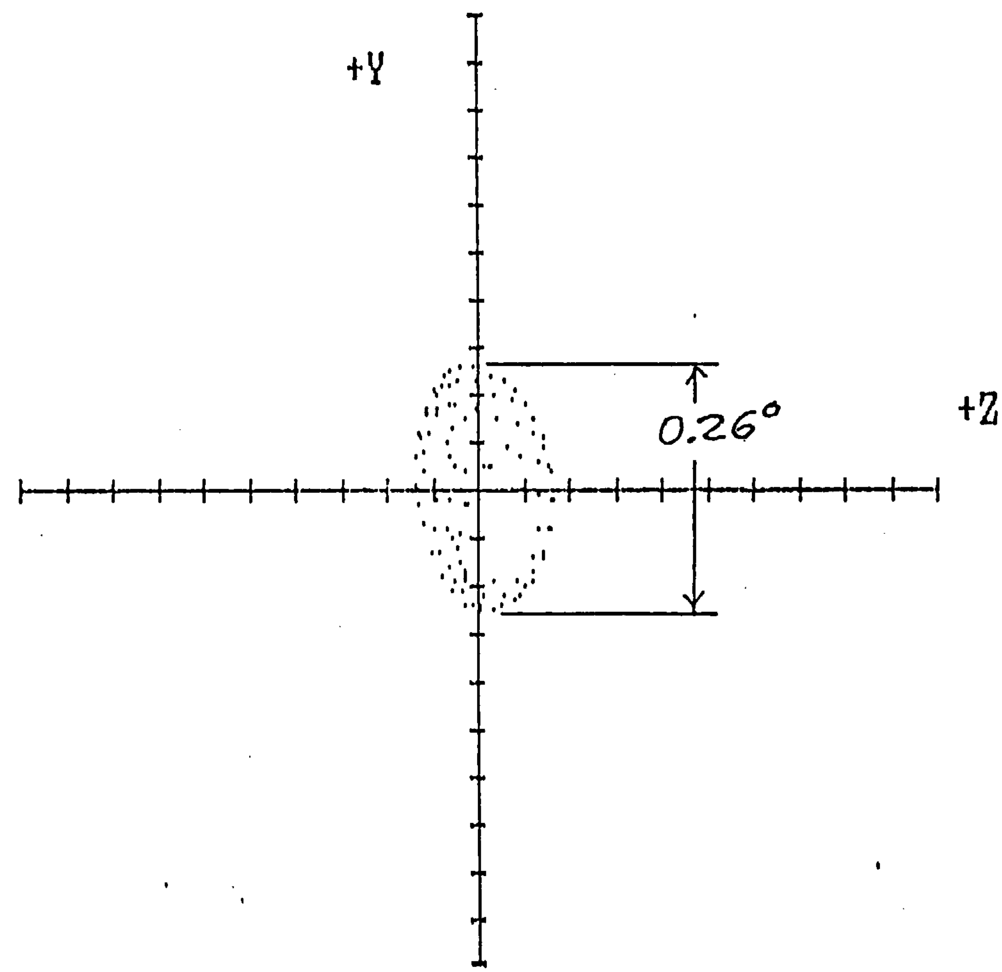


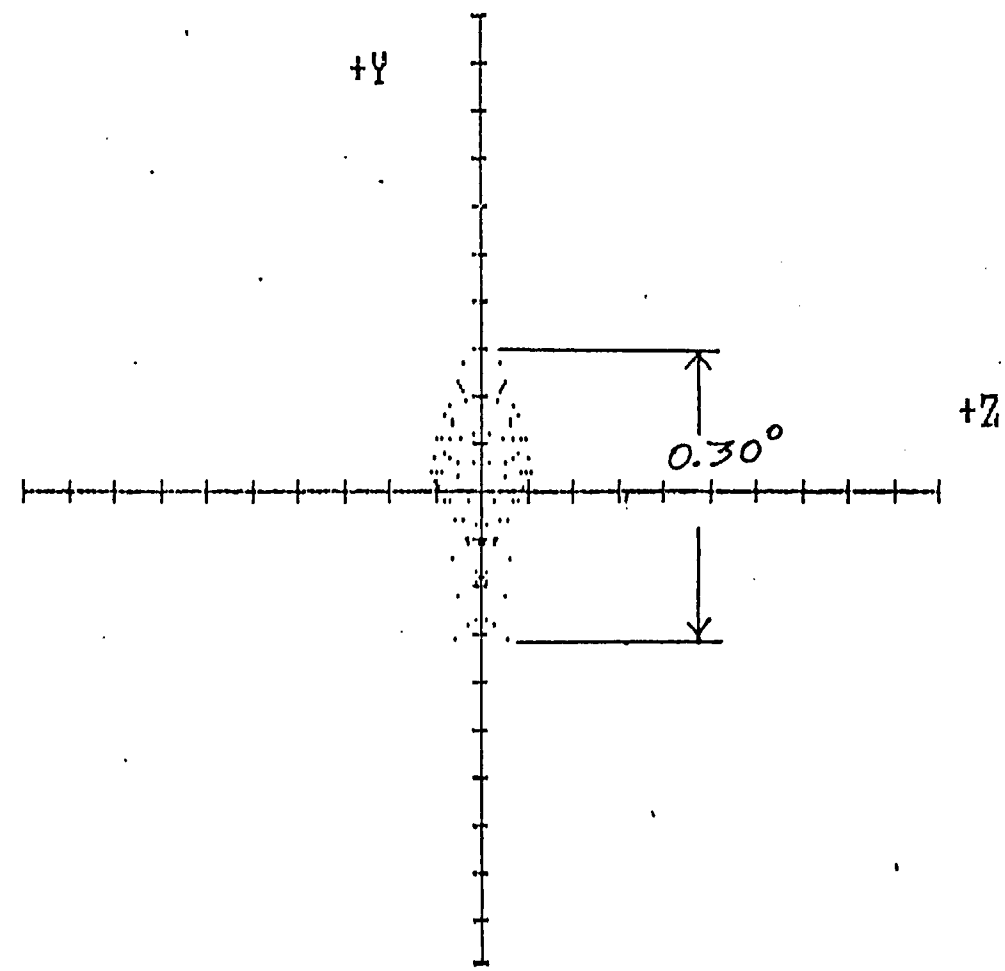
IMAGE AT LOWER RIGHT CORNER OF 8 FUV

MAGE AT UPPER CORNER OF B FOV

FIGURE 5

Data file name melsys5
Date 03-11-1987
Time 15:28:30
Wavelength 1
Image Plane 121.61
Field angles
T-plane -7.249
S-plane 0

limits Y direction
-3.952263
-5.952263
limits Z direction
1
-1
Dimensions in mm
rays/color 100



OPTICAL SYSTEM DATA SHEET

SYSTEM DESCRIPTION: MELCO Earth Sensor Assembly

PROJECT NO. AECZ

BY R. A. Gontin DATE 9-10-1986

SURF. NO.	mm. RADIUS & TOL In.	CC or CX	mm. CLEAR APER In.	mm. THK & TOL In.	MATERIAL	SURF. CODE	IRREG (fr.)	COATING TYPE	COATING R_{MAX}	COATING $\lambda(\mu)$
1	106.71 ± 0.10	CX	58.5			80-50	2	SEE NOTE		2
				4.12 ± 0.04	Ge					
2	151.72 ± 0.20	CC	58.5			80-50	2	SEE NOTE		2
3										
4										
5										
6										
7										
8										

REMARKS:

① Surface #1 is tilted relative to surface #2 at a wedge angle of 1.54° ± 2 min

② The coating specifications are the same as those for 257302-2003-1 (i.e. the standard ESA objective lens).

BARNES ENGINEERING COMPANY DWG NO.

STAMFORD, CONNECTICUT SHEET OF

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	July 1995	Contractor Report

4. TITLE AND SUBTITLE
Earth Sensor Assembly for the Tropical Rainfall Measuring Mission Observatory (Final Report)

5. FUNDING NUMBERS
Contract: NAS5-32463

6. AUTHOR(S)
PI: Steven Prince and James Hoover

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
EDO Corporation
Barnes Engineering Division
Shelton, CT 06484

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
NASA Aeronautics and Space Administration
Washington, D.C. 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
CR-203668

11. SUPPLEMENTARY NOTES
Technical Monitor: Rodriquez-Alvar

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category: 18
Report available from the NASA Center for AeroSpace Information,
800 Elkridge Landing Road, Linthicum Heights, MD 21090; (301) 621-0390.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

EDO Corporation/Barnes Engineering Division (BED) has provided the TRMM Earth Sensor Assembly (ESA), a key element in the TRMM spacecraft's attitude control system. This report documents the history, design, fabrication, assembly, and test of the ESA.

14. SUBJECT TERMS
TRMM, design, fabrication, test, spacecraft, Earth Sensor Assembly

15. NUMBER OF PAGES
57

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited